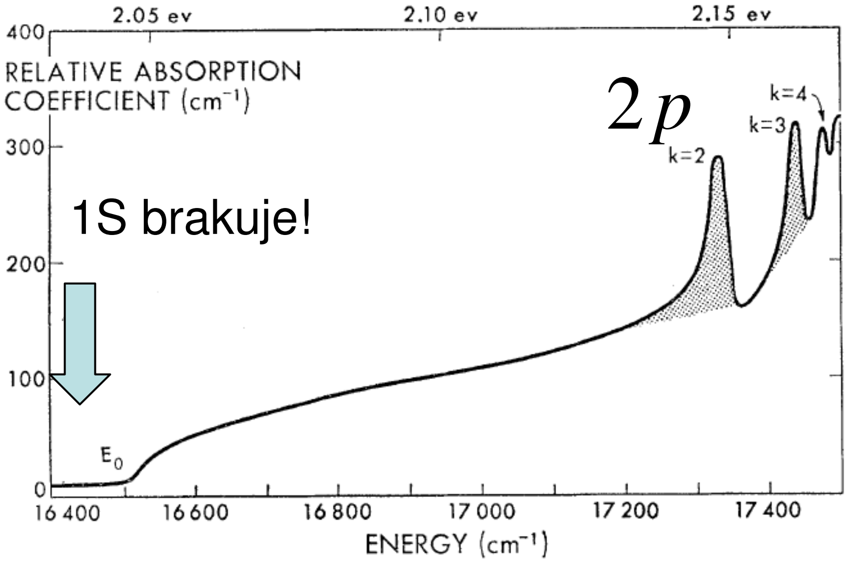
Ekscytony w Cu_2O

Cu_2O – przerwa prosta wzbroniona



1S brakuje!

FIG. 2. Relative absorption coefficient as a function of photon energy in cm⁻¹ of Cu_2O at 4.2°K.

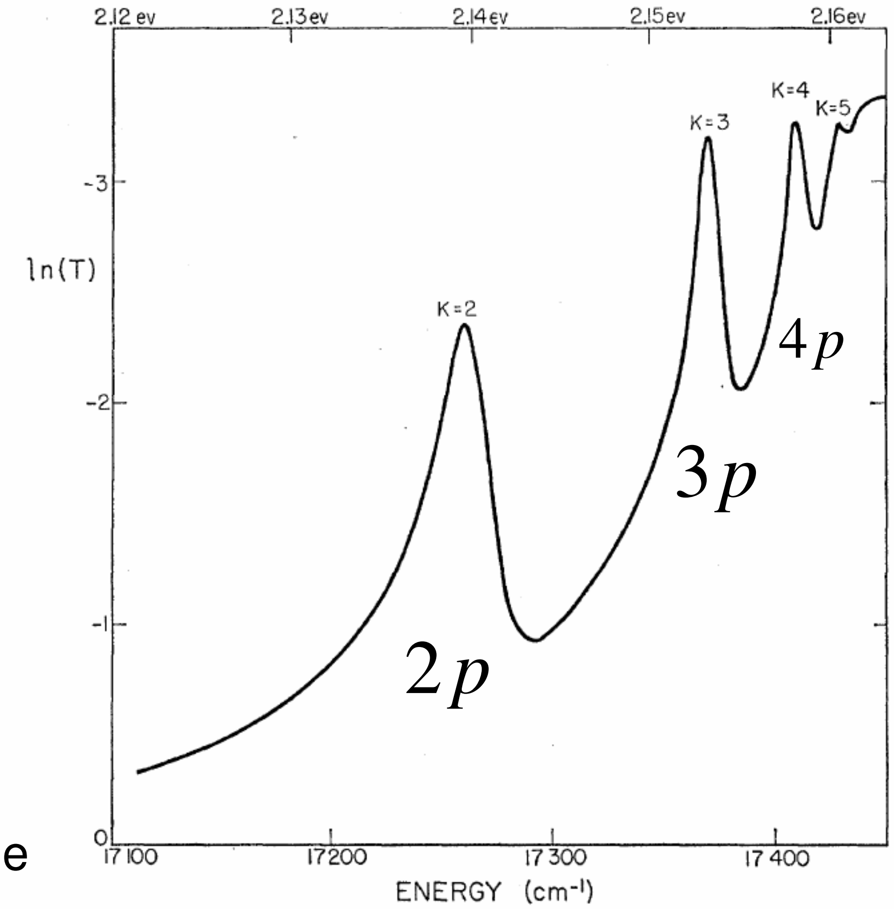


FIG. 6. The logarithm of the transmission as a function of photon energy of a Cu_2O sample at 77°K, showing the details of the yellow series of exciton lines.

$$\alpha_n \sim \frac{n^2 - 1}{n^5}$$

Przejście wzbronione dla n=1

$$E_n = (2.166 - 0.097/n^2)eV \quad n = 2,3,\ldots$$

P. Baumeister, Phys. Rev **121**, 359 (1963)

Transmisja ekscytonowa w GaN

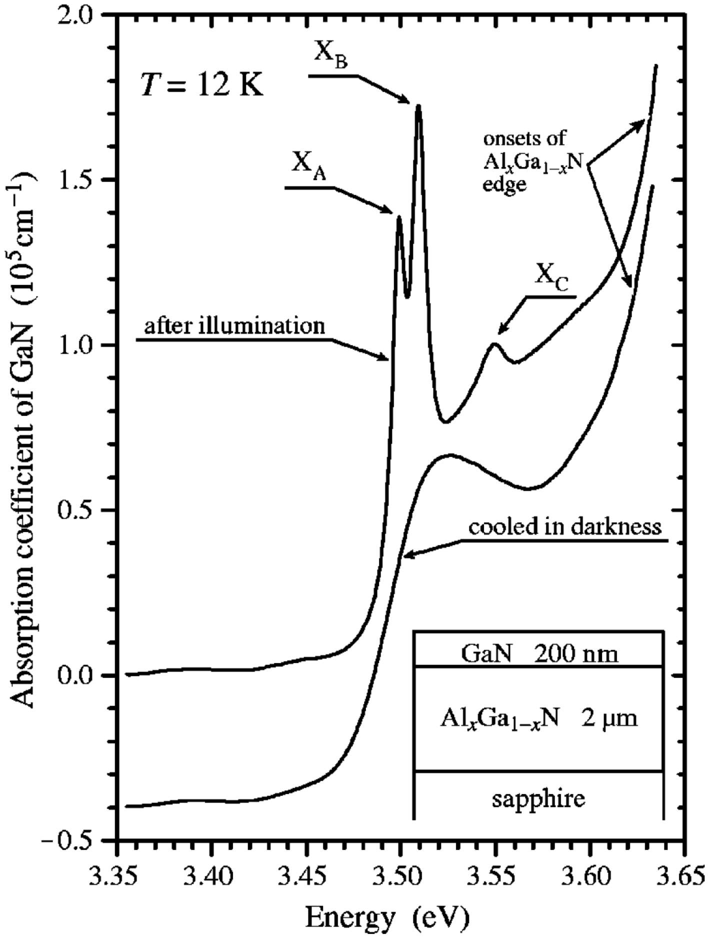


FIG. 1. Two spectra of the fundamental absorption edge of GaN measured in the same GaN/AlGaN heterostructure at the same temperature of 12 K. The broad one was measured after the sample had been cooled in darkness from 300 to 12 K. The sharp one was measured after the sample had been illuminated at the low temperature. The broad spectrum was shifted by -0.4×10^5 cm^{-1} for clarity of presentation.

Problemy:

- pola elektryczne (np. wokół dyslokacji),
- niejednorodne naprężenia

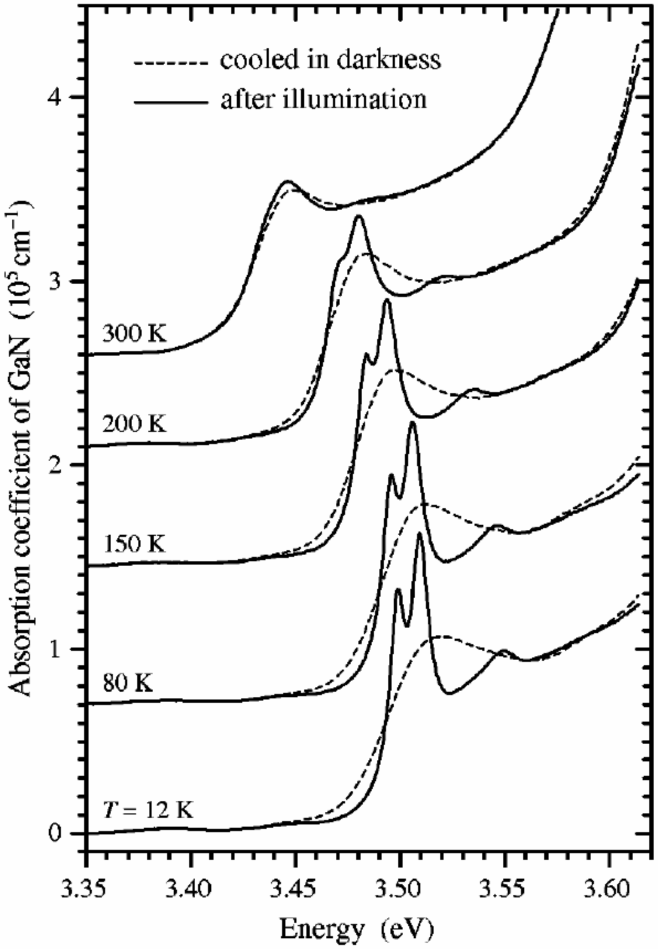
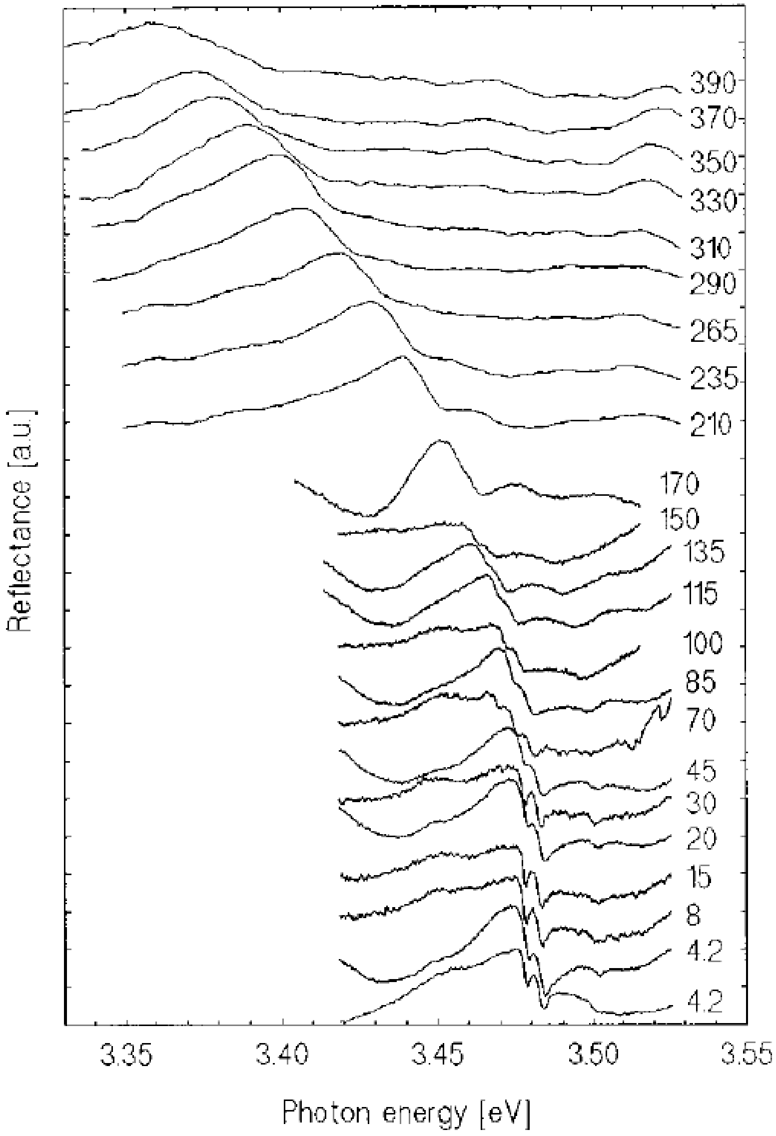
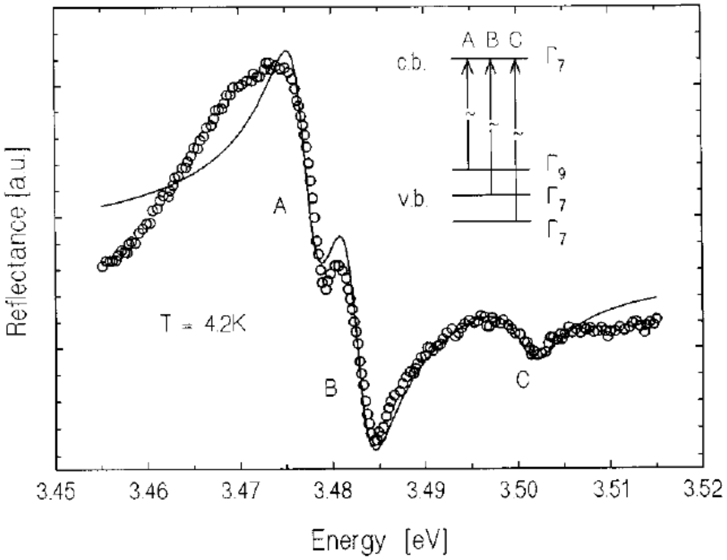


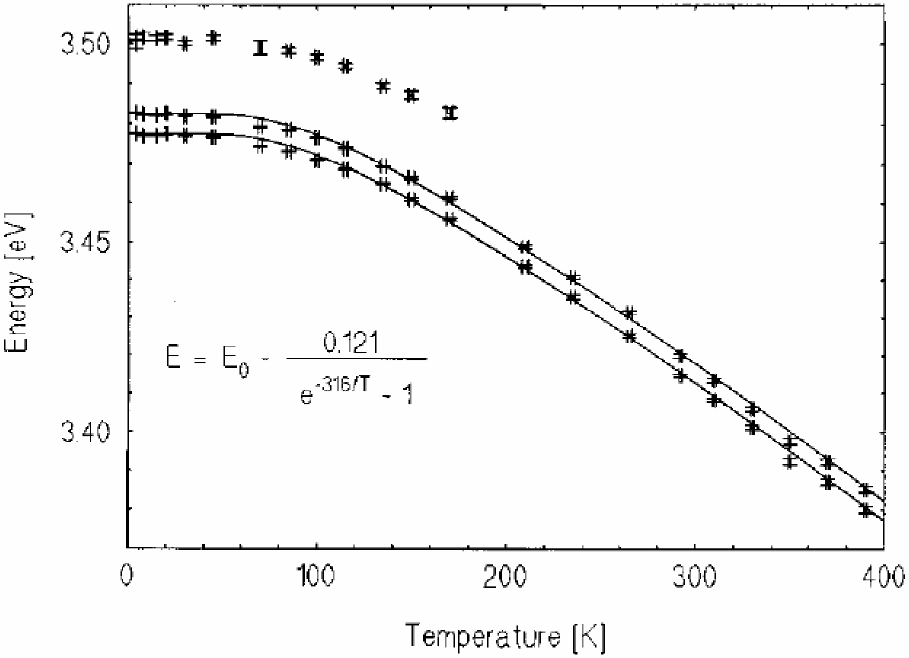
FIG. 2. Light-induced metastable narrowing of the fundamental absorption edge of GaN measured in a GaN/AlGaN heterostructure at five different temperatures between 12 and 300 K. The spectra were shifted vertically for clarity of presentation.

P. Trautman et al. APL **83**, 3510 (2003)

Pierwsze pomiary odbicia na próbkach homoepitaksiajnych GaN







E_A, E_B, E_C, Δ_{SO}, Δ_{CF}

K. Korona et al. APL **69**, 788 (1996)

Polariton ekscytonowy

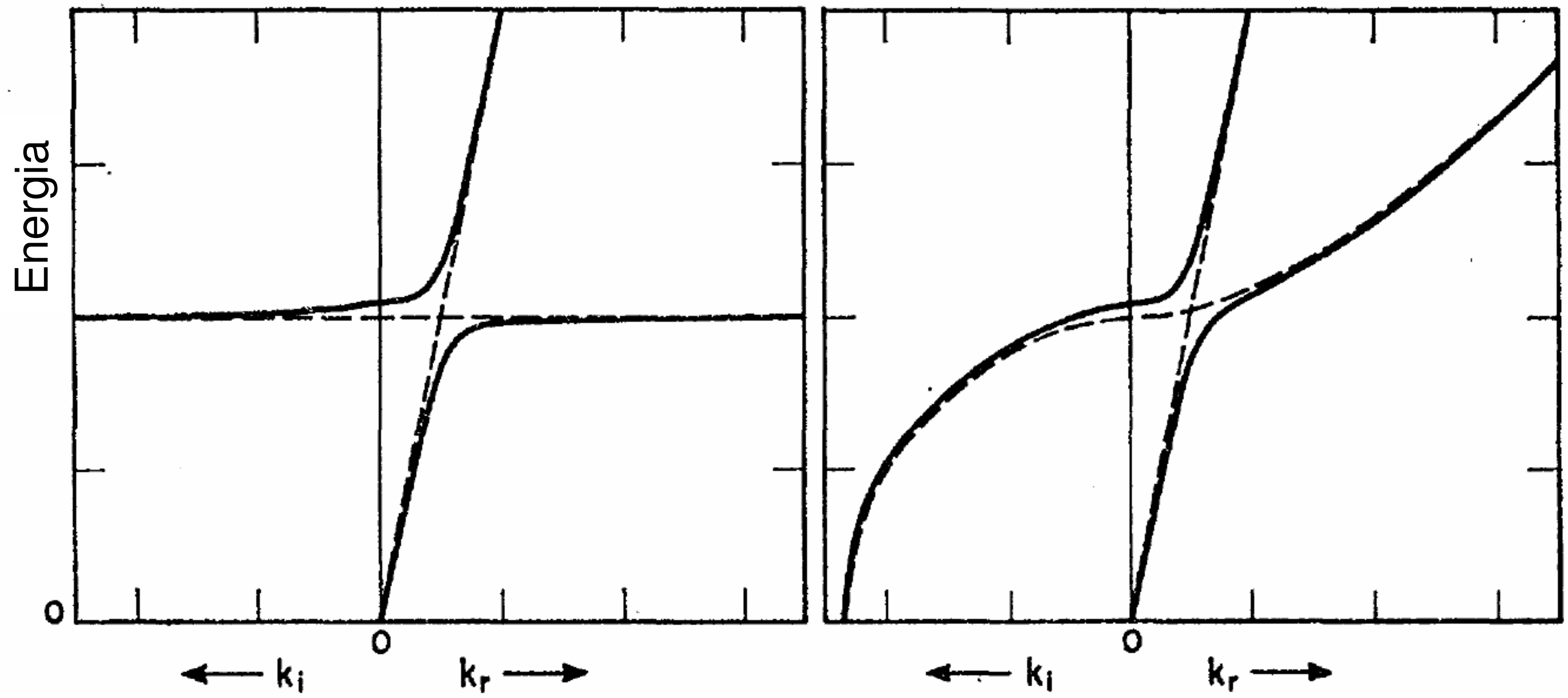
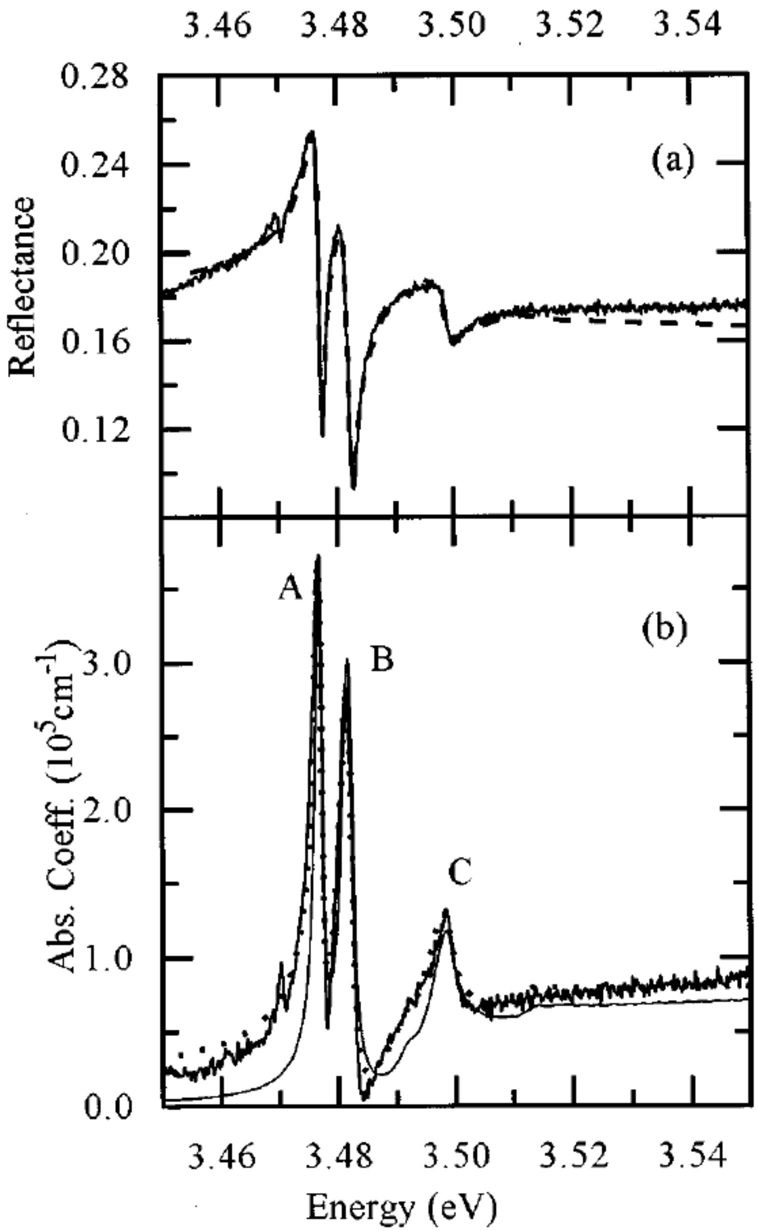


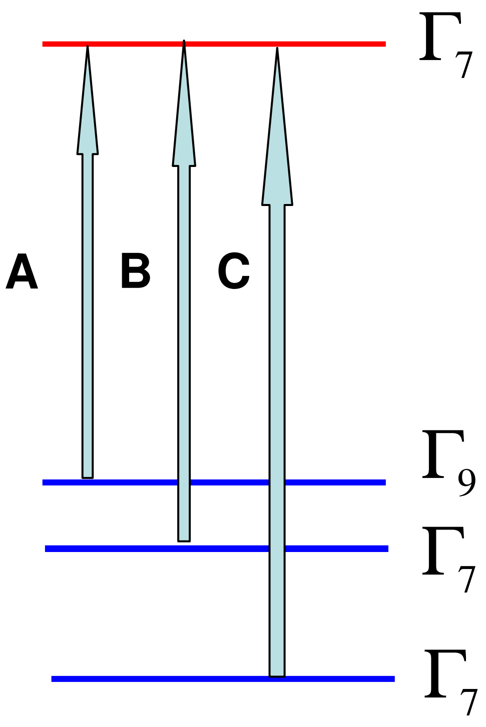
FIG. 2. The frequency wave-vector dispersion relation for the transverse normal modes of light coupled to a classical dielectric (graph at left) and a dielectric having spatial resonance dispersion (at right). No damping is included. The normal mode wave vectors are in either case either purely real or purely imaginary, and are plotted to the right or left accordingly. The dashed lines show the dispersion relations for α_0=zero; the solid lines for a finite α_0. Parameters have been chosen to display clearly the differences between the models.

J.J. Hopfield & D. J. Thomas Phys. Rev. **132**, 563 (1963)

Analiza polaritonowa widm odbicia w GaN



W widmie odbiciowym pojawiły się struktury odpowiadające trzem rodzajom ekscytonów swobodnych w GaN



R. Stępniewski et al. PRB 56, 15151 (1997)

Polaritony w GaN

$$\omega_X = \omega_{TX} + \frac{\hbar k^2}{2M},$$

$$\frac{\partial^2 P}{\partial t^2} + \omega_X^2 P = \omega_X^2 \alpha_X E - \gamma_X \frac{\partial P}{\partial t},$$

$$\varepsilon^* \frac{\partial^2 E}{\partial t^2} - c^2 \Delta E = -4\pi \frac{\partial^2 P}{\partial t^2},$$

E – pole elektryczne fotonu

P – wkład do polaryzacji pochodzący od ekscytonów

ε^* - stała dielektryczna ośrodka

$$\varepsilon^*(\omega) = \varepsilon_0^* + \sum_{n=2}^{\infty} f_n \frac{\omega_n^2}{\omega_n^2 - \omega^2 - i\,\delta\omega}$$

$$+ \int_{E_{\mathrm{gap}}}^{E_{\max}} f_s \frac{\omega_s^2 ds}{\omega_s^2 - \omega^2 - i\,\delta\omega}\,.$$

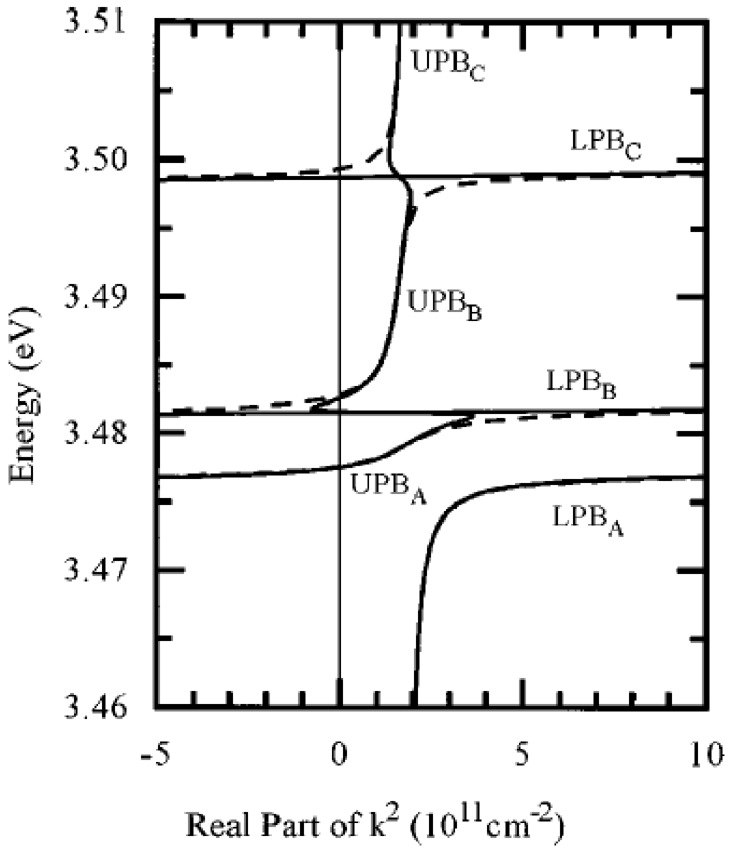
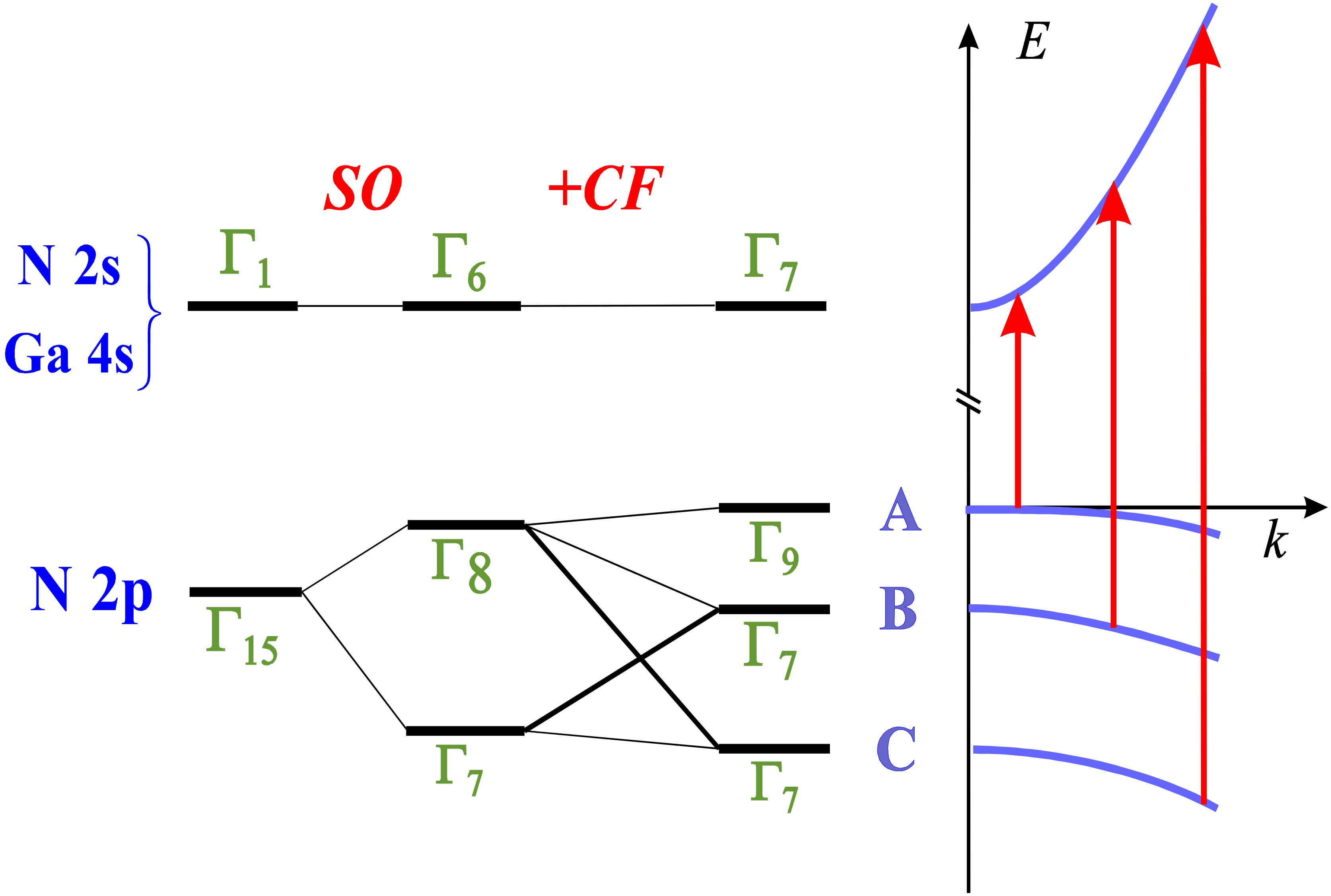


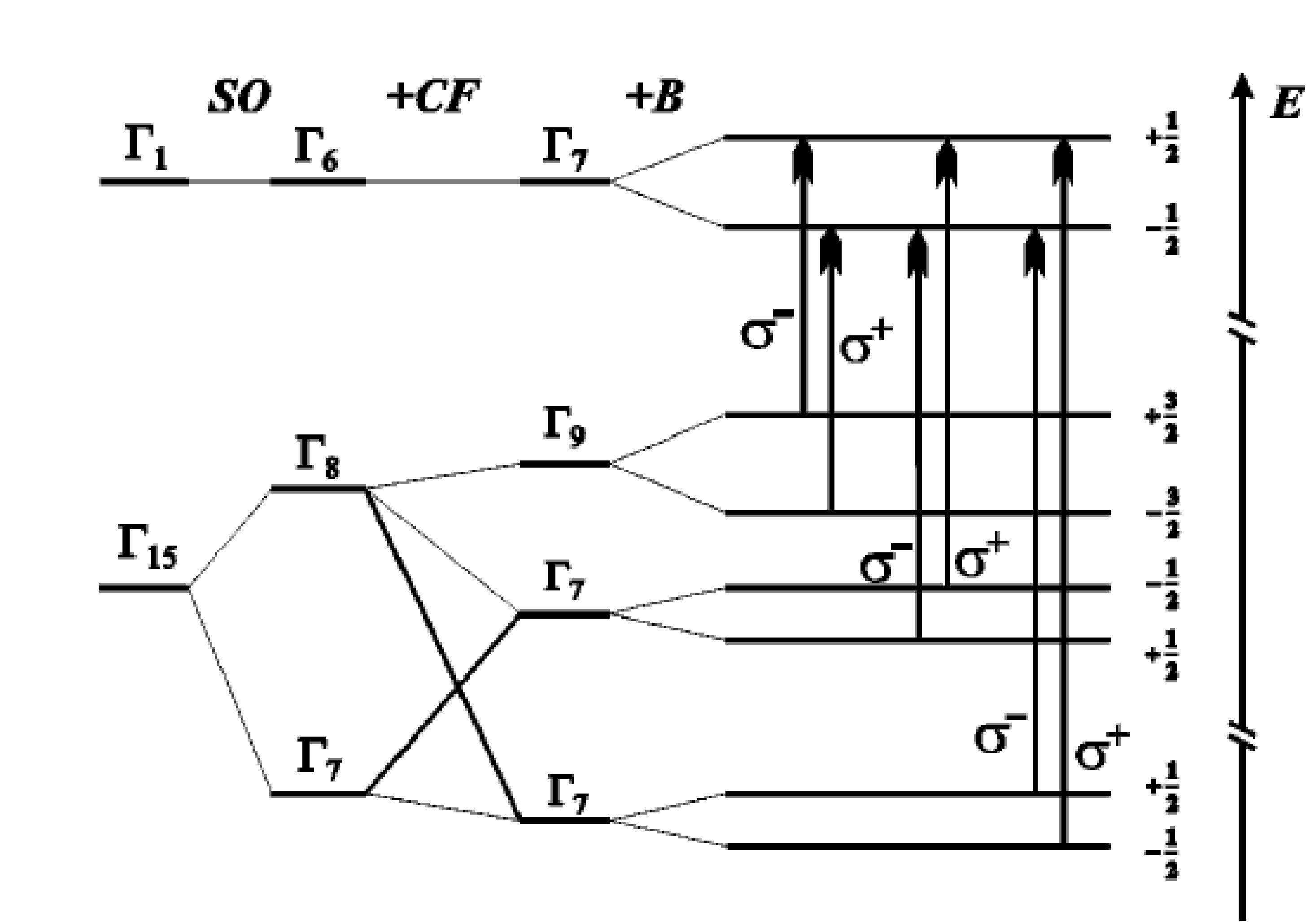
FIG. 1. Solid line: the calculated polariton dispersion curves of GaN. Four branches arising from photon coupling with A, B, and C excitons are labeled: LPB$_X$ for the lower polariton branch of exciton X, and UPB$_X$ for the upper polariton branch of exciton X. Three excitons lines originate from the crystal-field and spin-orbit splitting of the valence band. For comparison, curves calculated for $\gamma_X = 0$ are plotted with a dashed line.

R. Stępniewski et al. PRB 56, 15151 (1997)

Struktura pasmowa GaN



Schemat rozszczepień w polu magnetycznym pasma przewodnictwa i pasma walencyjnego w GaN (k=0)



Umożliwia identyfikację symetrii stanów pasmowych!

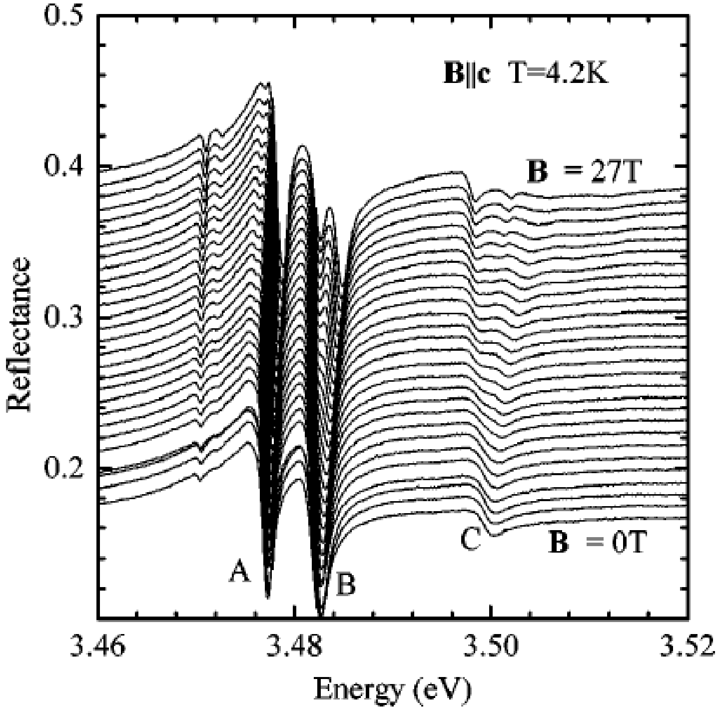
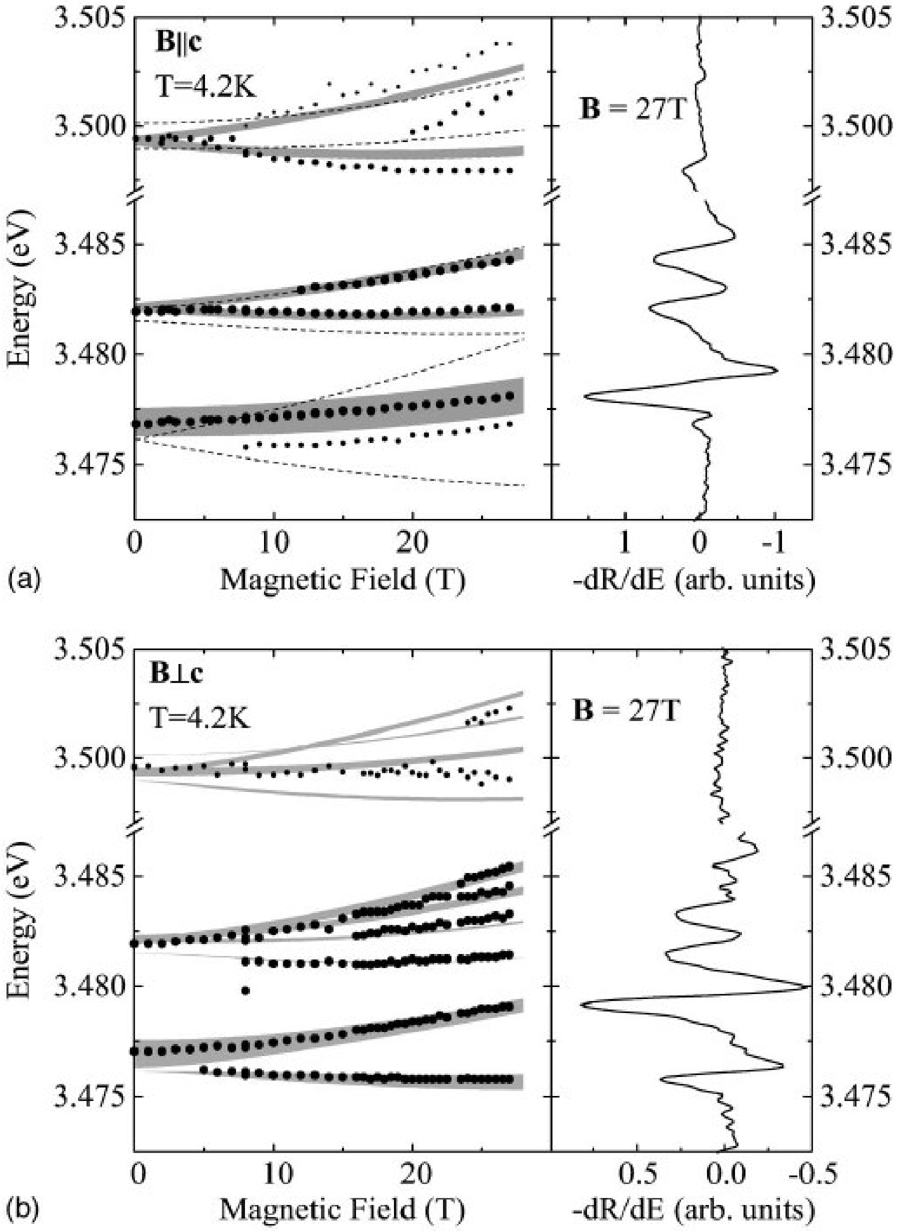


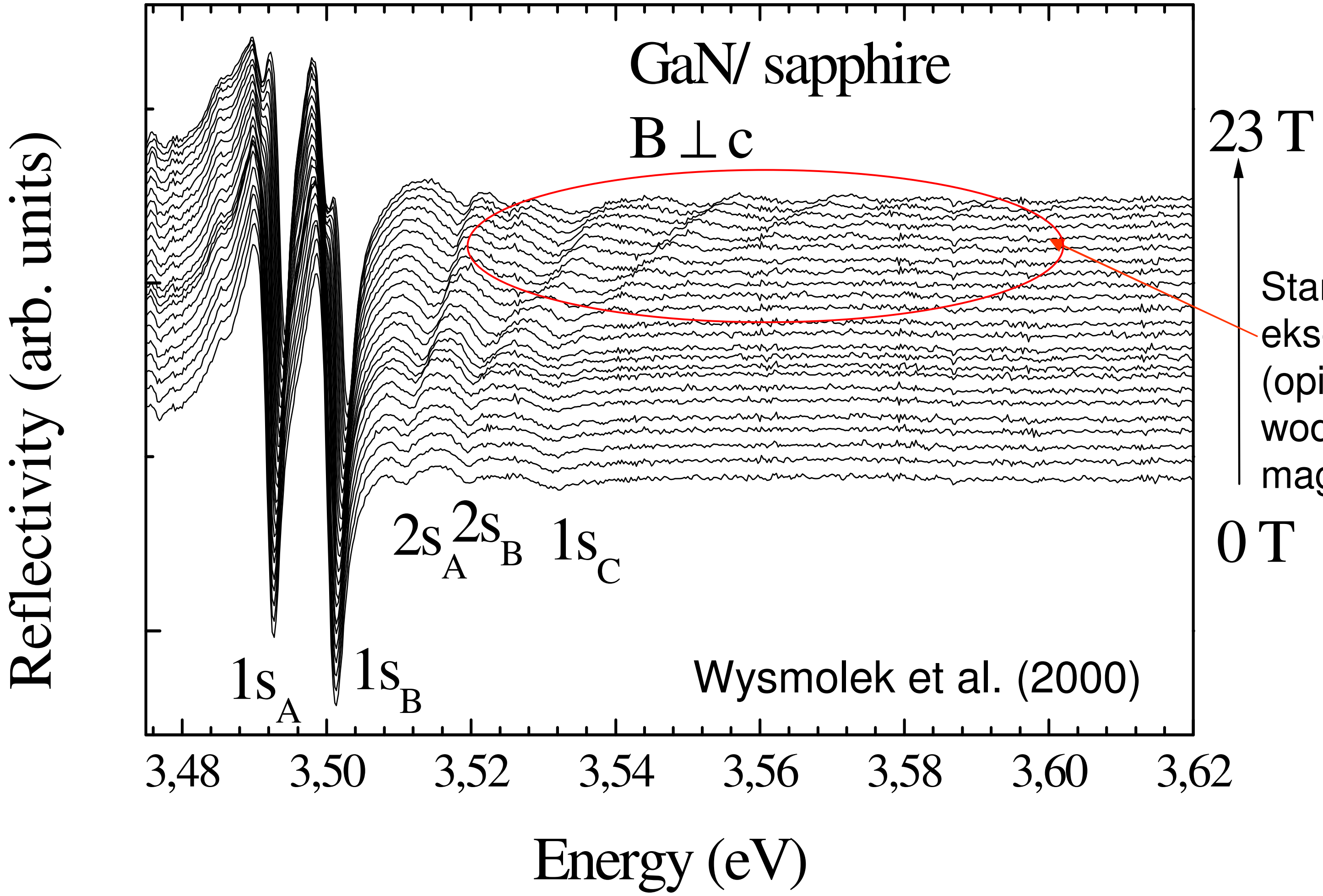
FIG. 1. Magnetoreflectance spectra of GaN measured in magnetic fields up to 27 T applied along the **c** axis of the wurtzite crystal. For clarity, subsequent spectra are shifted vertically.



- symetria stanów ekscytonowych
- parametry pasmowe
  (wzorzec GaN)

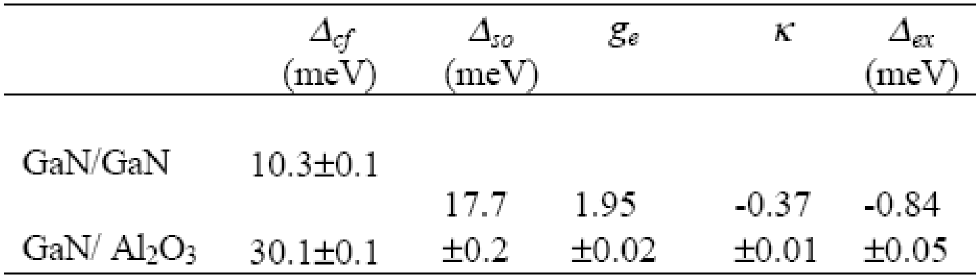
R. Stepniewski et al. PRB **60**, 4438 (1999)

GaN na Al_2O_3 – naprężony, inne wzajemne położenia ekscytonów A, B, C



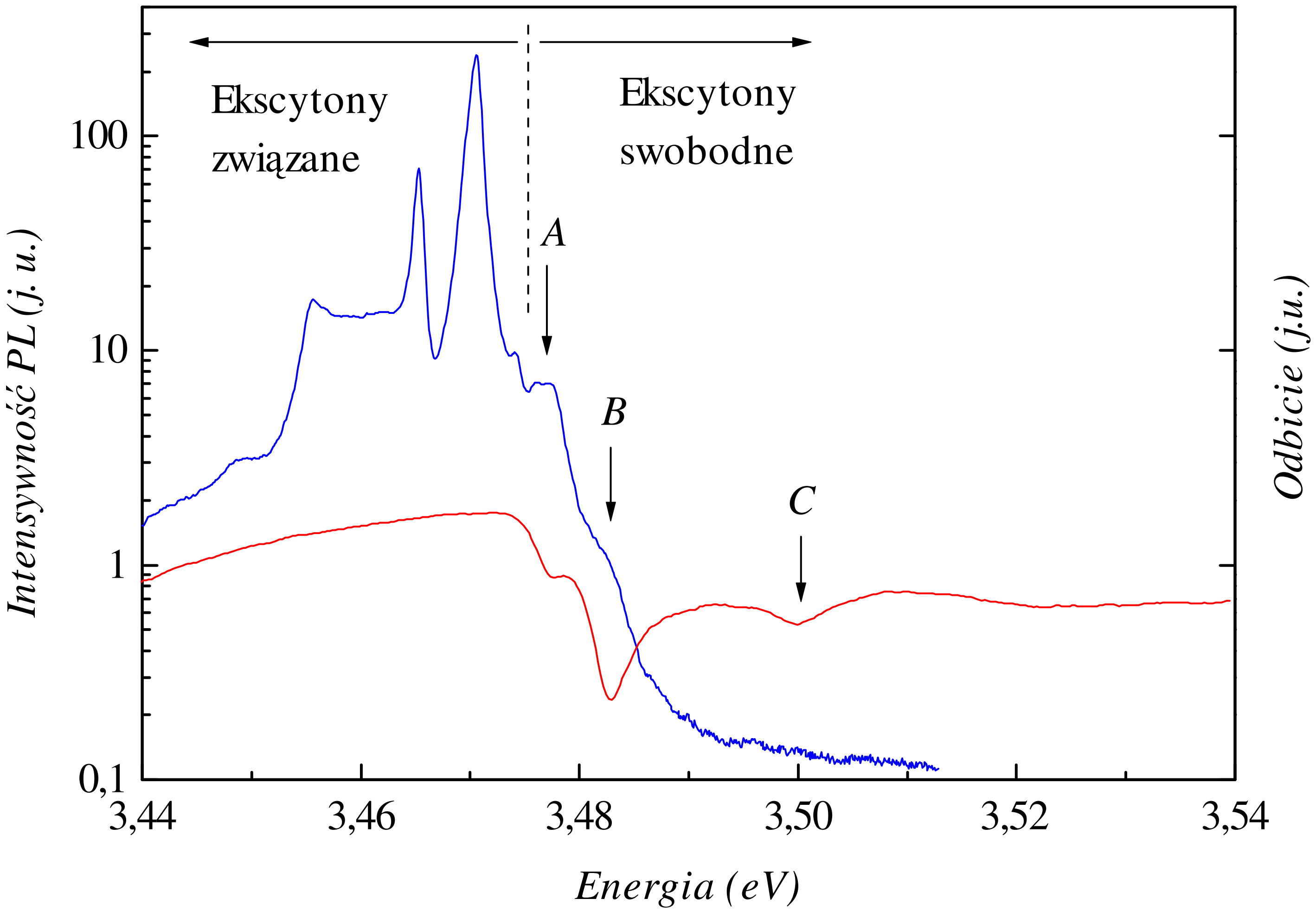
Stany wzbudzone ekscytonów A, B (opis – atom wodoru w polu magnetycznym)

Parametry naprężonego GaN



	Δ_{cf} (meV)	Δ_{so} (meV)	g_e	κ	Δ_{ex} (meV)
GaN/GaN	10.3±0.1	17.7 ±0.2	1.95 ±0.02	-0.37 ±0.01	-0.84 ±0.05
GaN/ Al_2O_3	30.1±0.1				

Porównanie luminescencji i odbicia w GaN



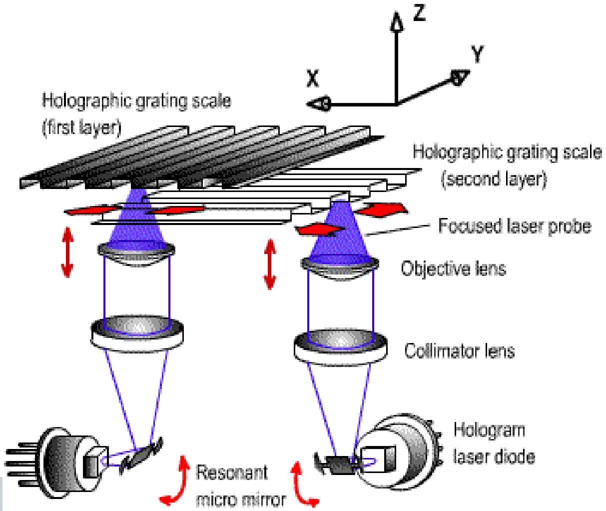
Ekscytony swobodne lepiej widać w absorpcji i odbiciu
Ekscytony związane dominują w luminescencji

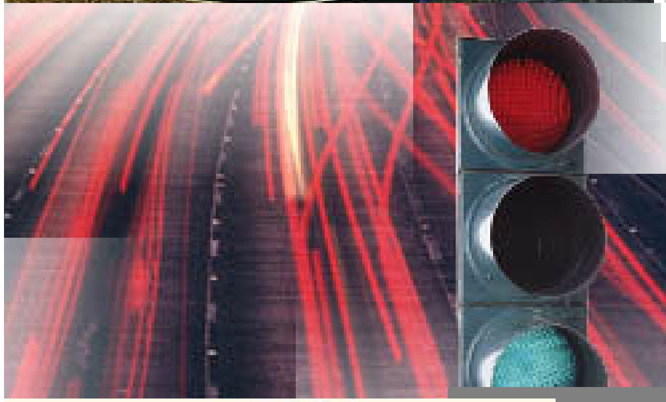
Przejścia ekscytonowe

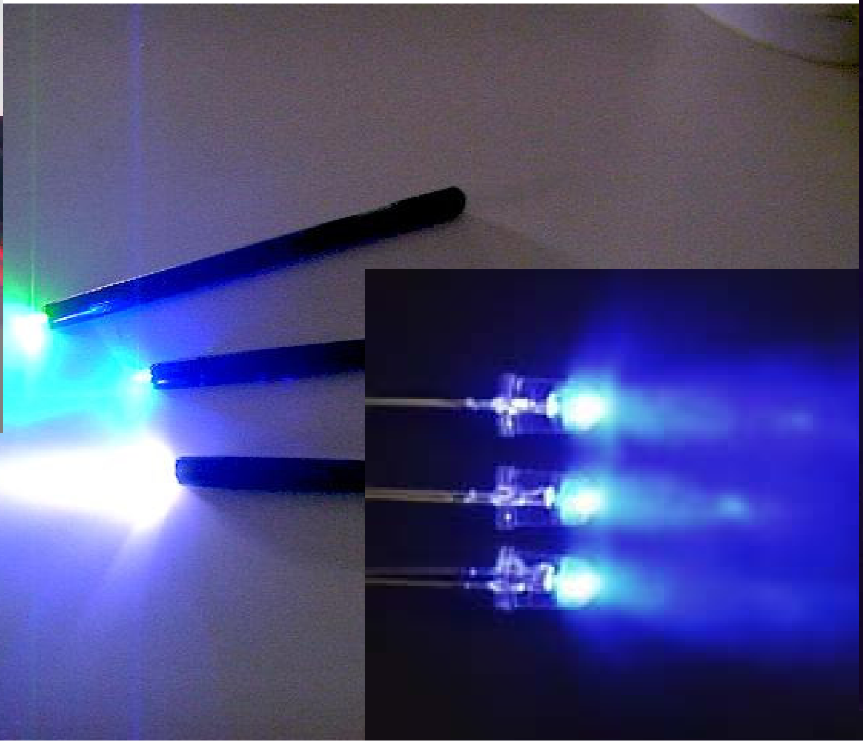
Obserwacja: wysokiej jakości próbki o niewielkiej koncentracji domieszek i defektów

- **ekscytony swobodne**
  - dobrze widoczne w absorpcji, odbiciu, fotoprzewodnictwie
  - słabo widoczne w luminescencji (problem z odebraniem pędu przez foton)
- ekscytony związane
  - słabo widoczne w absorpcji, odbiciu (mała liczba domieszek)
  - dobrze widoczne w luminescencji (pęd ekscytonu przejmowany jest przez domieszkę, nie ma problemu z emisją fotonu, w wyniku zderzeń ekscytony tracą energię i wiążą się w domieszkami tworząc kompleksy ekscytonowe)

Niebieska optoelektronika

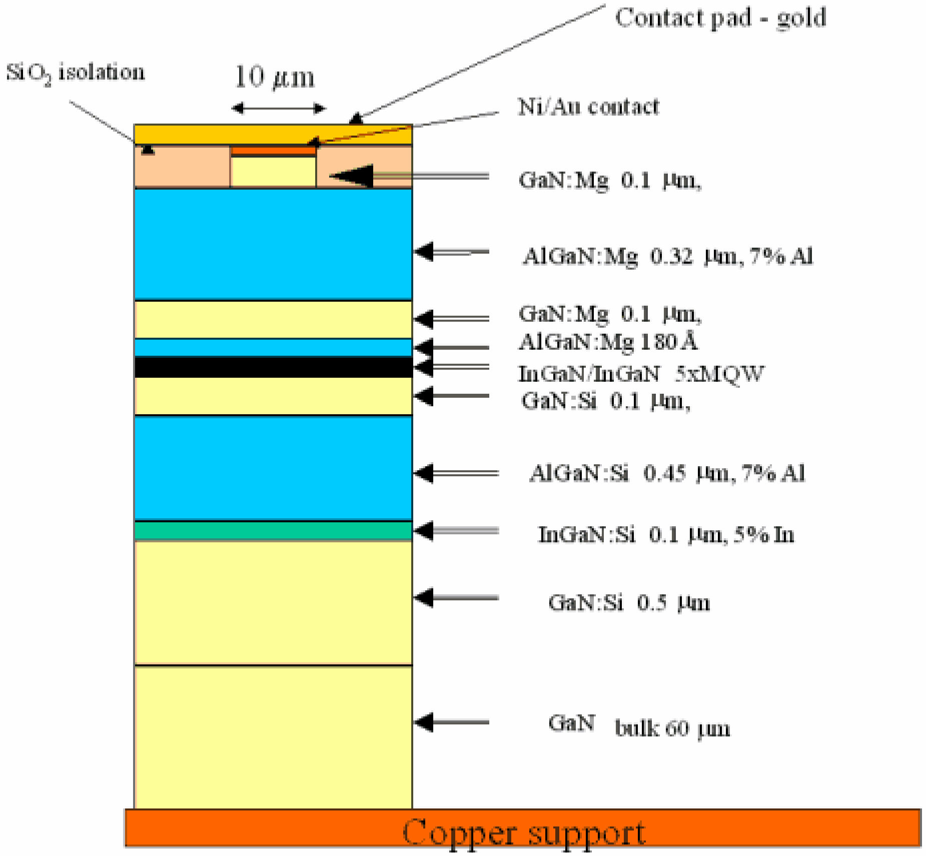




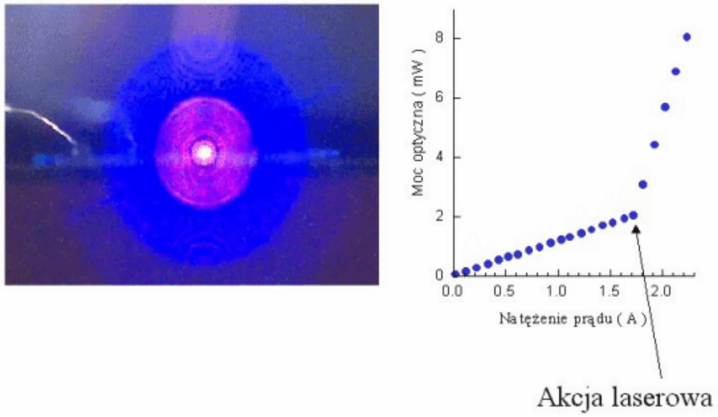


Niebieski laser

Schemat diody laserowej UT 106

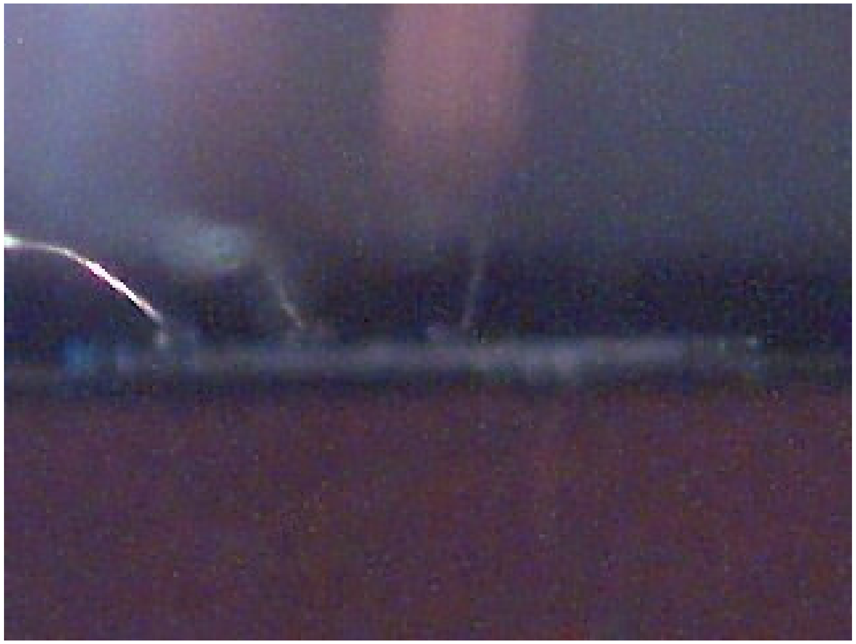


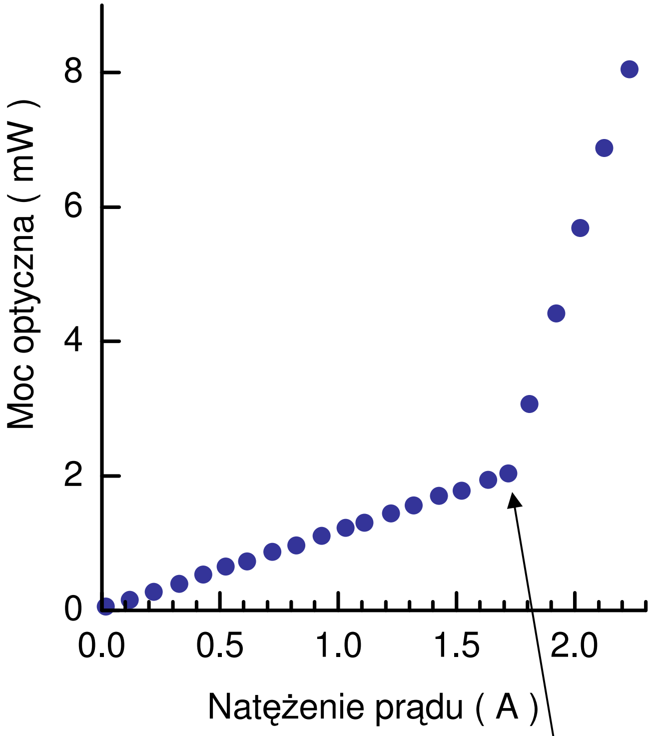
Elektryczne pobudzanie struktury laserowej „UT 106”



Elektryczne pobudzanie struktury laserowej „Unipress 106”

unipress

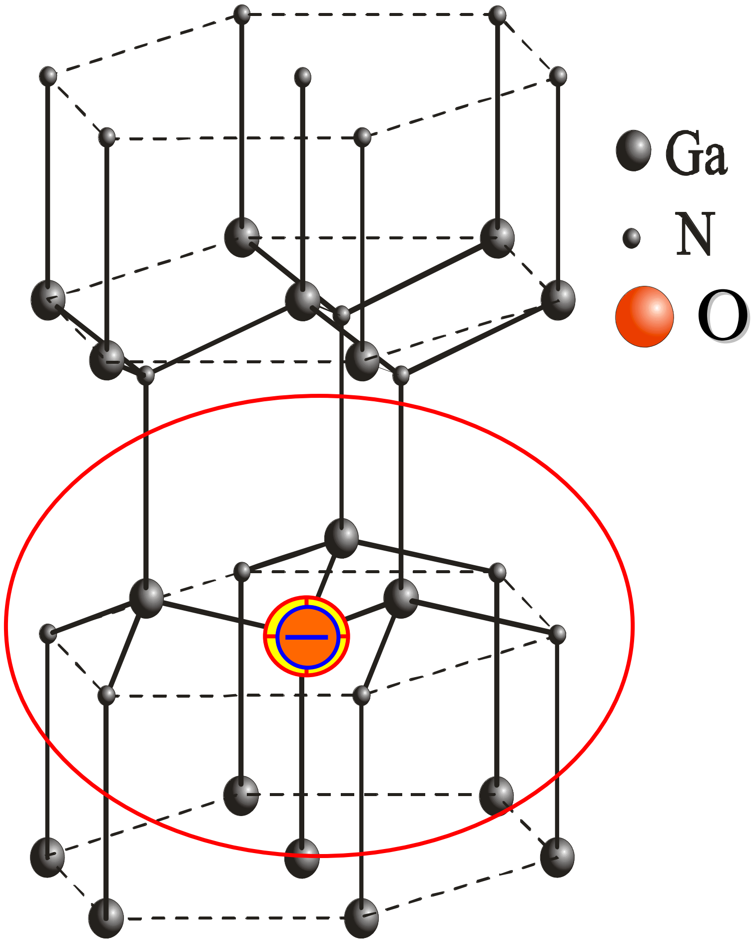




Akcja laserowa

Domieszkowanie…

m*



Neutralny donor
w przybliżeniu masy efektywnej

$$\left(-\frac{\hbar^2}{2}\Delta-\frac{e^2}{4\pi\varepsilon_0\quad r}\right)\Phi_n(\mathbf{r})=E\;\Phi_n(\mathbf{r})$$

m* ε_s

$$E_n=-\frac{R*}{n^2};\;\; n=1,2,\ldots\;;\; R*=13.6eV\,\frac{m*}{\varepsilon_s{}^2}$$

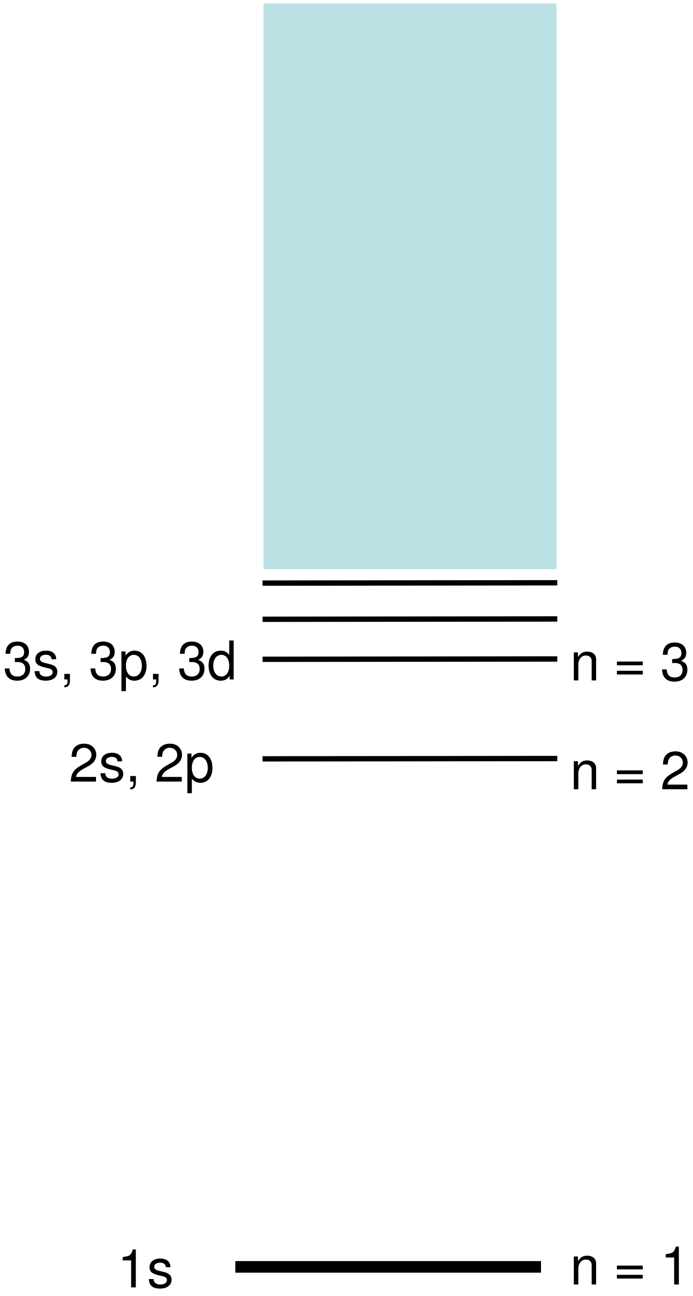
Problem bardzo zbliżony do rozważań ekscytonowych!

J. Luttinger and W. Kohn, Physical Review **97** ,869 (1955)

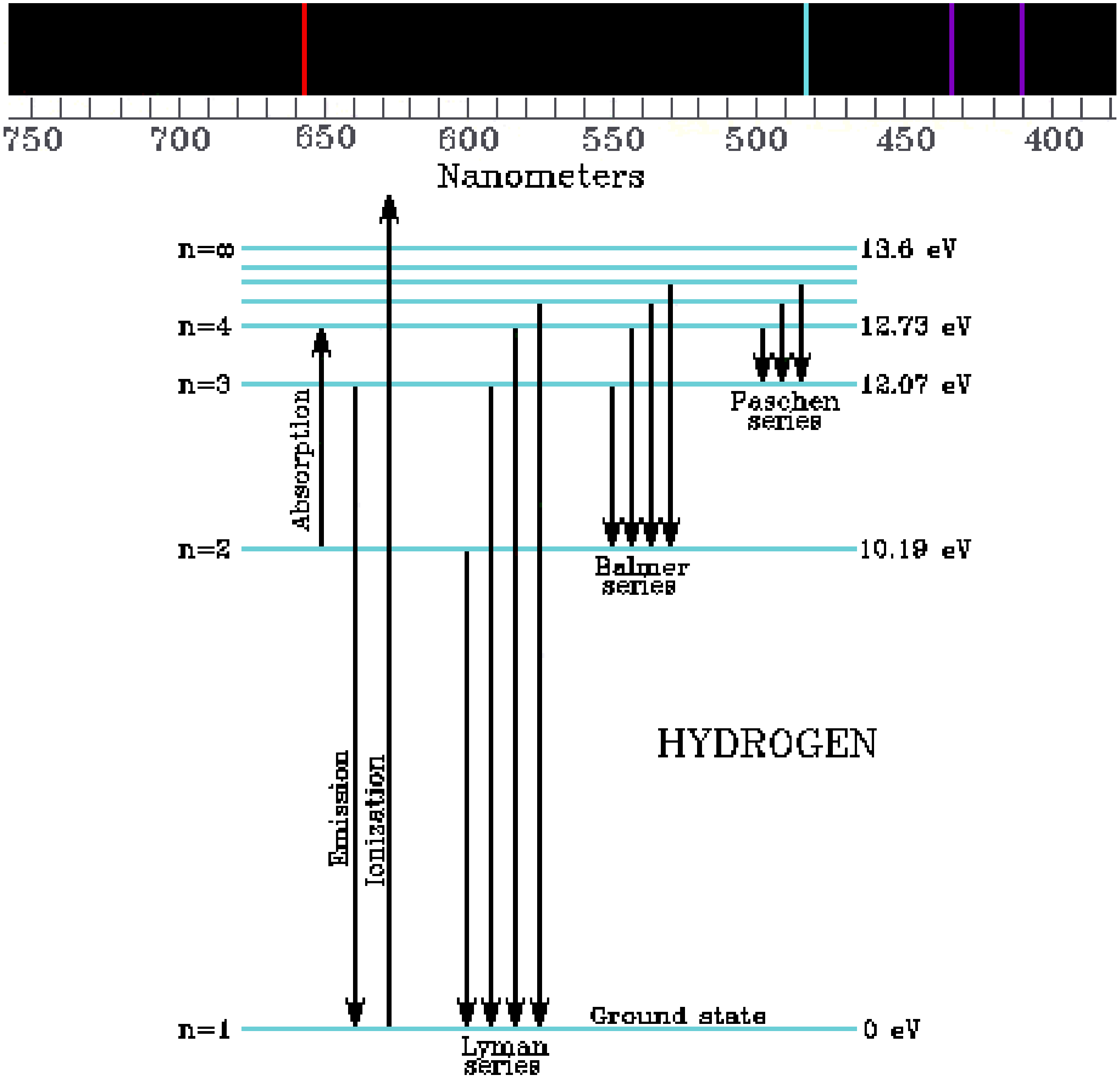
Atom wodoru

$$E_n = -\frac{m_0 e^4}{2(4\pi\varepsilon_0)^2\hbar^2}\frac{1}{n^2} = -R\frac{1}{n^2}$$

$R = 13{,}6$ eV



Widmo atomu wodoru



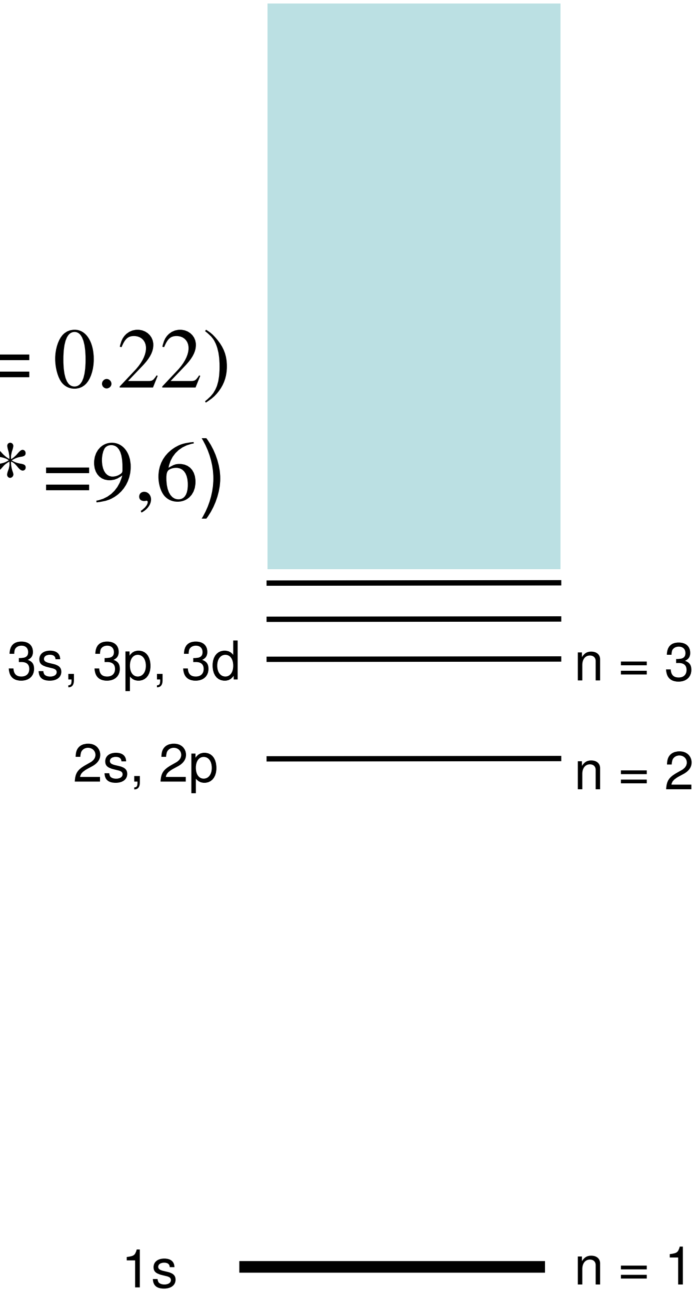
Donor

$m_0 \rightarrow m = m^* m_0$ (dla GaN $m^* = 0.22$)

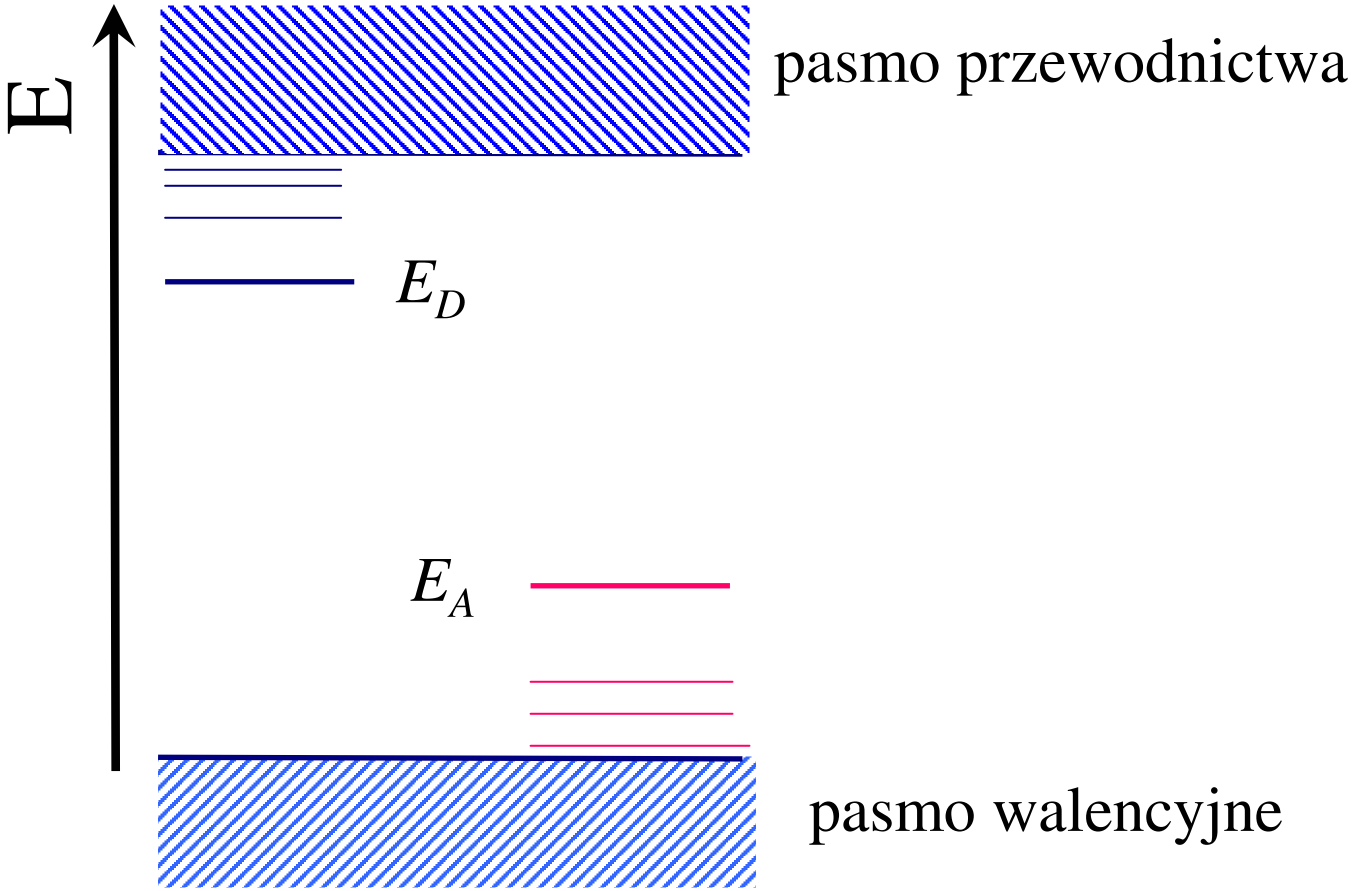
$\varepsilon_0 \rightarrow \varepsilon = \varepsilon^* \varepsilon_0$ (dla GaN $\varepsilon^* = 9,6$)

$$R^* = R \frac{m^*}{(\varepsilon^*)^2}$$

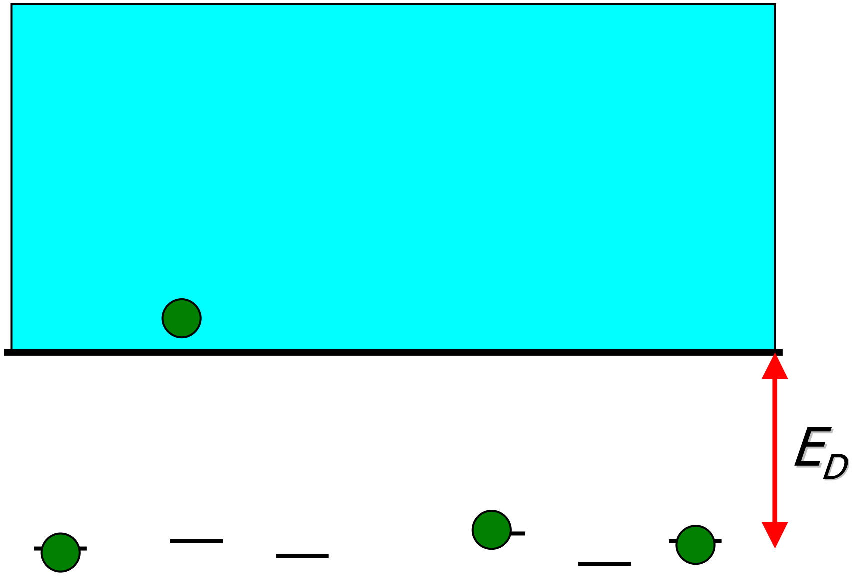
$R^* = 30$ meV

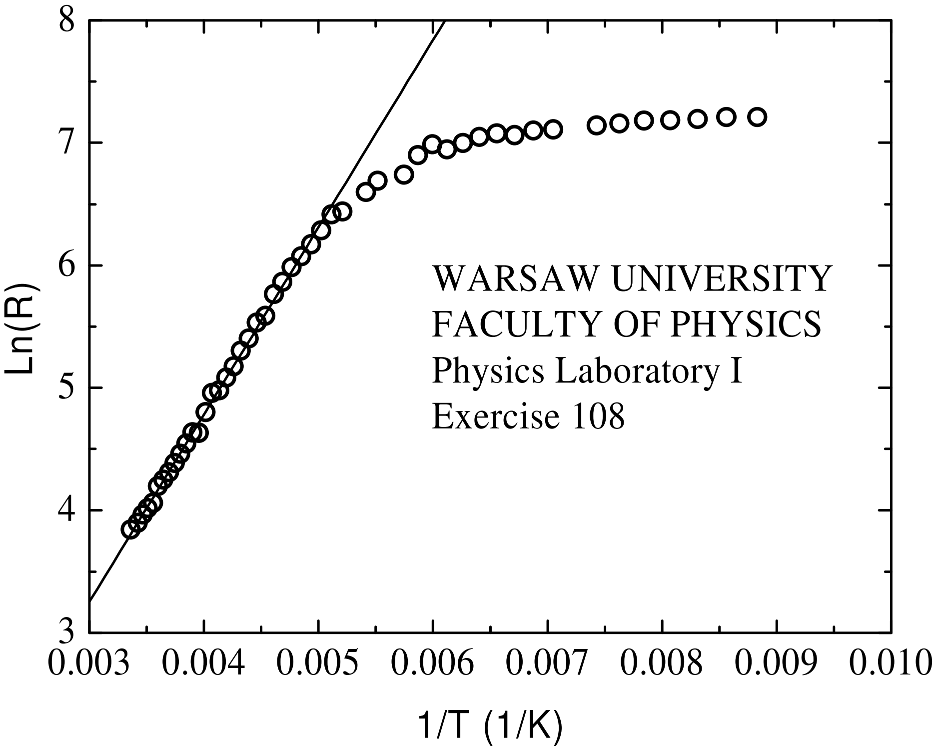


Stany domieszkowe



Energia wiązania donora

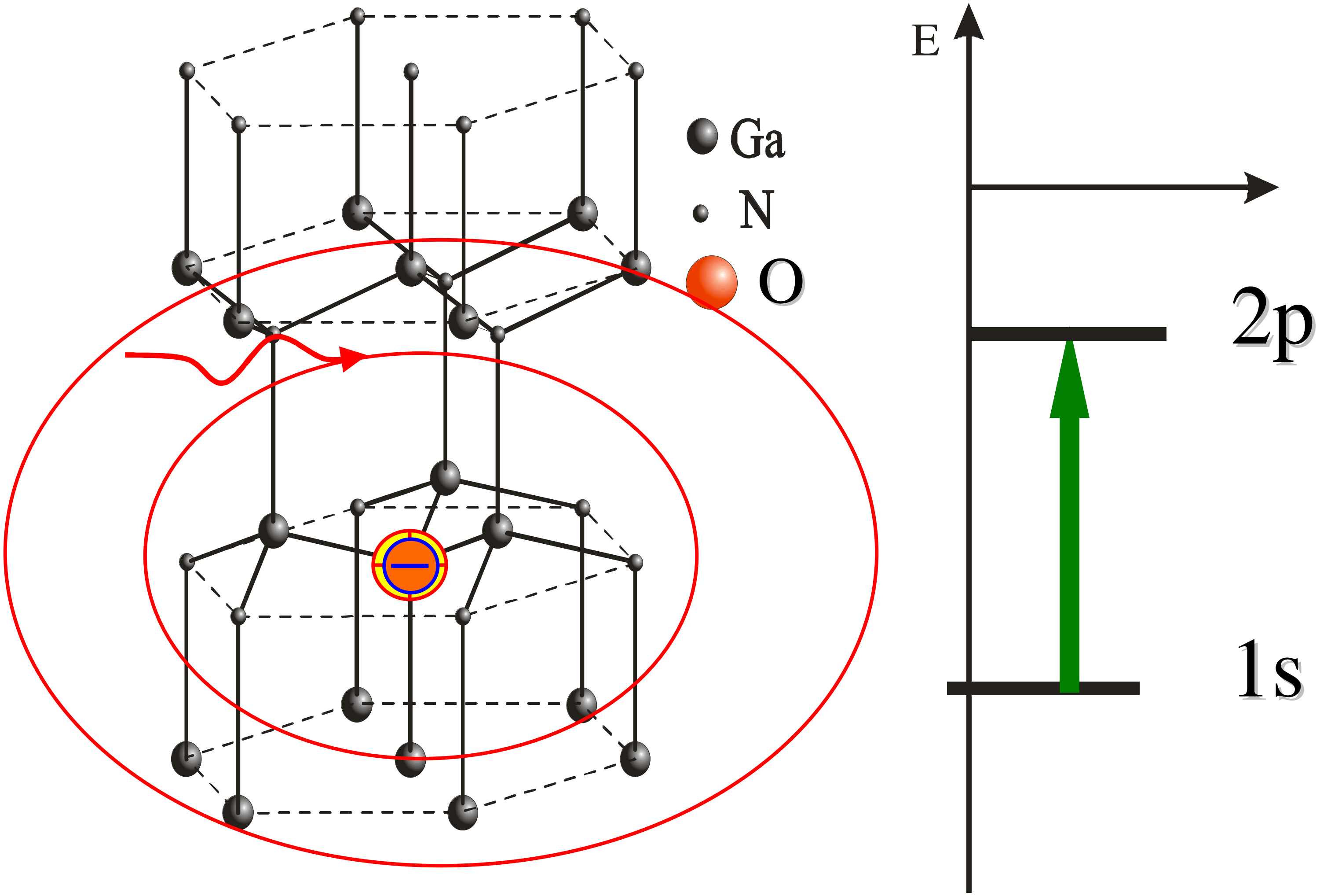




$$R=R_{\infty}\; exp(E_D\,/k_B T)$$

Neutralny donor

m*



Wodór w polu magnetycznym

$$\hat{H} = \frac{1}{2m^*}\left(\hat{\mathbf{p}} + e\mathbf{A}\right)^2 - \frac{e^2}{4\pi\varepsilon_0\varepsilon_s}\frac{1}{r}$$

$$\vec{A} = 1/2(\vec{B}\times\vec{r})$$

(Cechowanie cylindryczne)

Charakterystyczne jednostki długości i energii:

$$a^* = \frac{4\pi\hbar^2\varepsilon_0\varepsilon}{e^2 m^*} \qquad \mathrm{Ry}^* = \frac{m^* e^4}{2\hbar^2(4\pi\varepsilon_0\varepsilon_s)^2}$$

⇨

$$E_0 = 2Ry^*$$

$$\gamma = \frac{1/2\hbar\omega_c}{Ry^*}$$

We współrzędnych biegunowych (ρ,φ,z)

$$\boxed{\hat{H} = -\nabla^2 - \frac{2}{r} - i\gamma\frac{\partial}{\partial\varphi} + \frac{1}{4}\gamma^2\rho^2}$$

$$r = \sqrt{\rho^2 + z^2}$$

Rachunek wariacyjny

$$\Psi = \sum_j C_j\psi_j$$

Funkcje bazowe

$$\psi_i = \rho^{|m|} e^{i\varphi m} z^q e^{-\alpha_i\rho^2} e^{-\beta_i z^2}$$

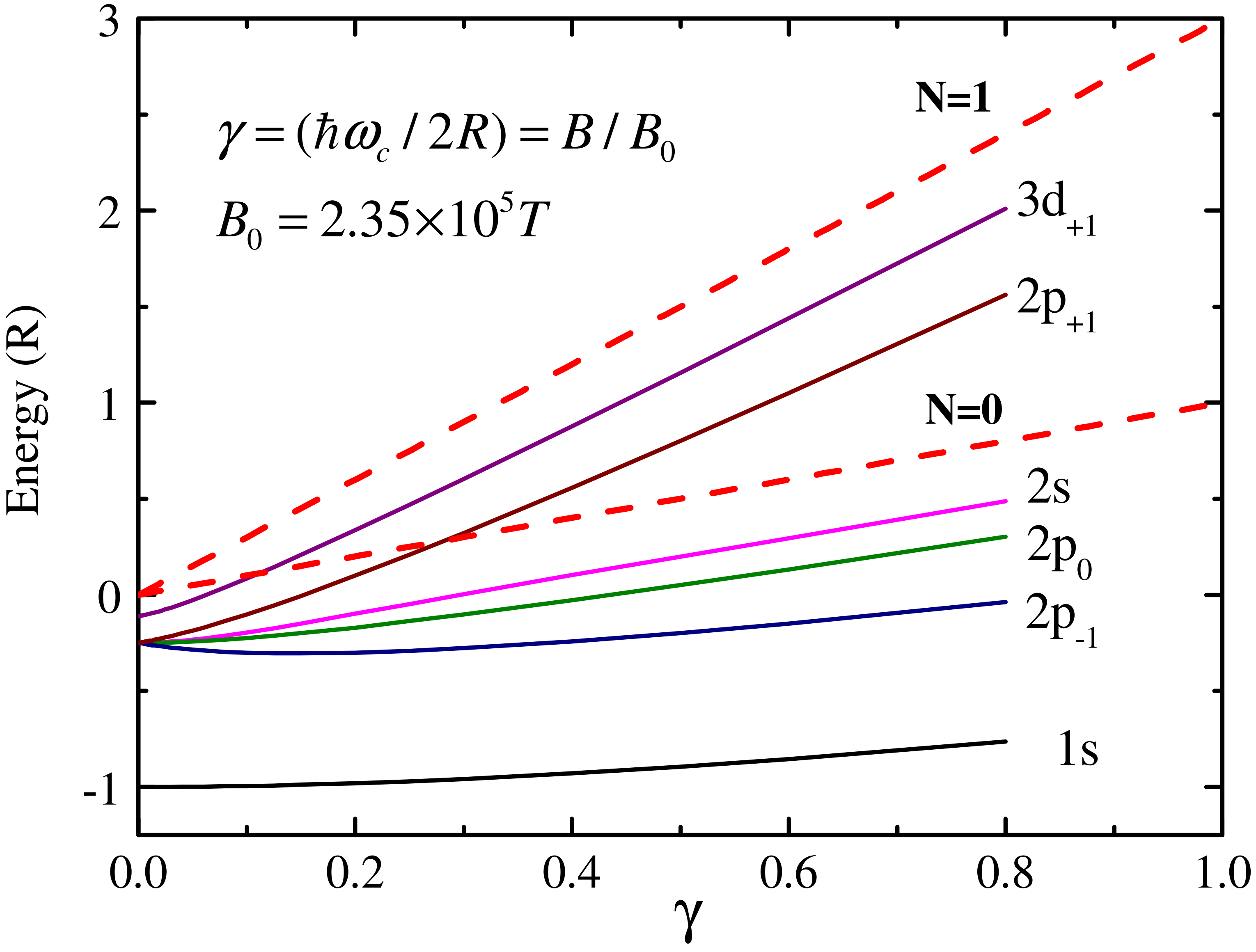
Symetria Hamiltonianu:

$$\boxed{E_{-|m|} = E_{|m|} - 2|m|\gamma}$$

P.C. Makado and N. C. McGill, J. Phys. C **19**, 873 (1986)

Wodór w polu magnetycznym

- P. C. Macado and N. C. McGill,
  J. Phys. C: Solid State Physics **19**, 873 (1986)
- W. Rösner, G. Wunner, H. Herold and H. Ruder,
  J. Phys. B: At. Mol. Phys. **17,** 29 (1984)
- A. V. Turbiner,
  J. Phys. A: Math. Gen. **17**, 858 (1984)
- Y. P. Kravchenko, M.A. Liberman, B. Johanson,
  PRB **54**, 287 (1996)



Y. P. Kravchenko, M.A. Liberman, B. Johanson, PRB **54**, 287 (1996)

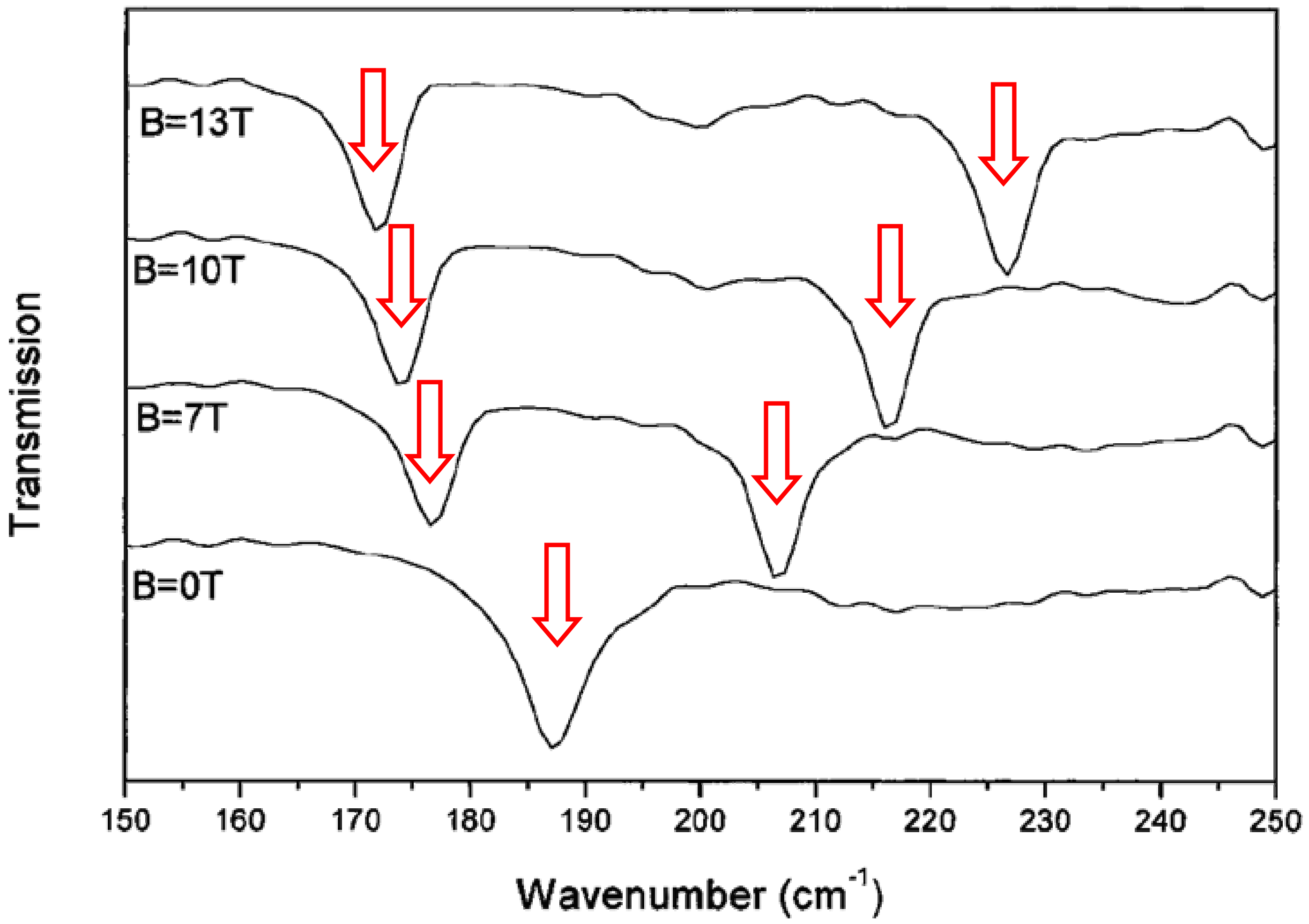


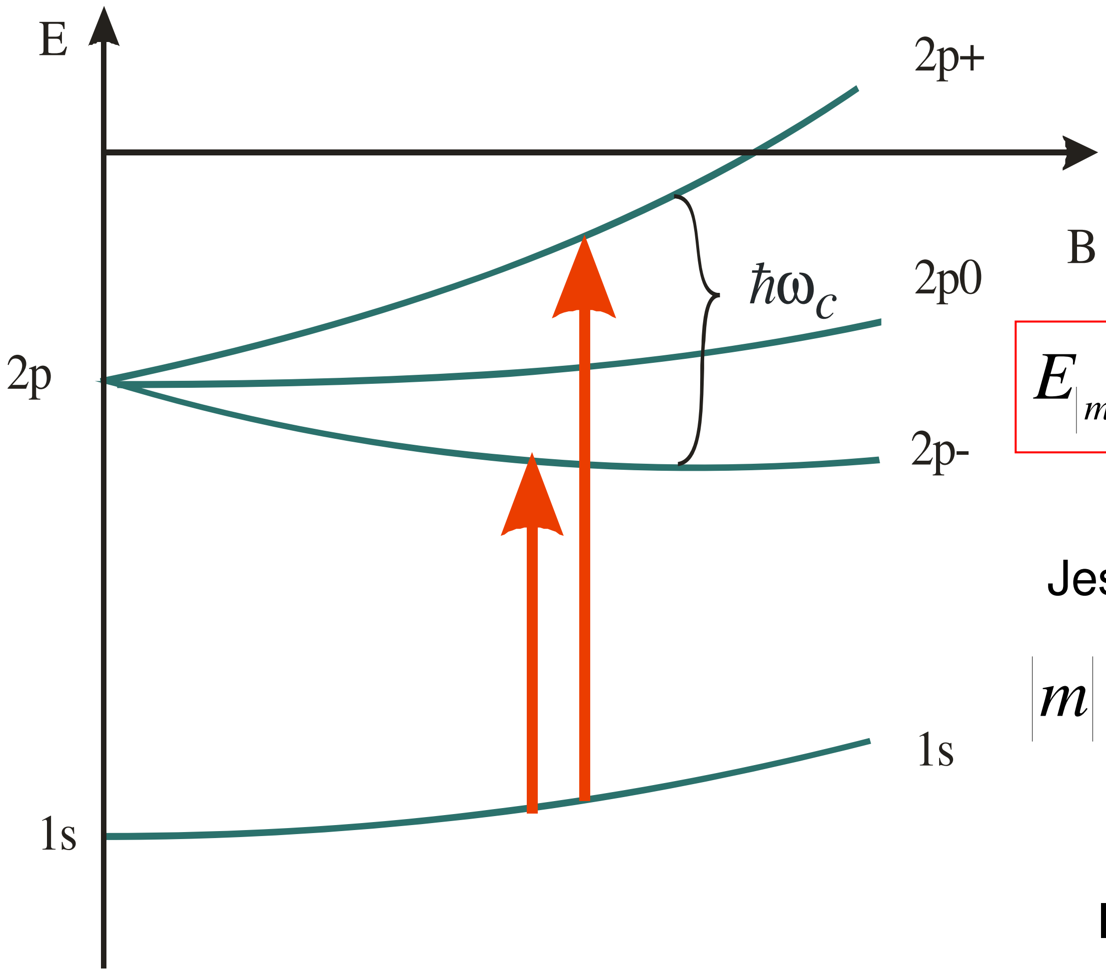
Fig. 1. Transmission spectra of an undoped GaN layer on sapphire, measured at 2K, normalised by the transmission of a sapphire slab identical to the substrate

„Far-Infrared Magnetospectroscopy of Shallow Donors in GaN”

A.M. Witowski et al., phys. stat. sol. (b) ***210****, 385 (1998)*

Transmisja w dalekiej podczerwieni

D^0



$$\boxed{E_{-|m|} = E_{|m|} - 2|m|\gamma}$$

$$\boxed{E_{|m|} - E_{-|m|} = 2|m|\gamma = |m|\hbar\omega_c}$$

Jeśli

$$|m| = 1 \qquad E_{2p_{+1}} - E_{2p_{-1}} = \frac{\hbar eB}{m^*}$$

Informacja o masie efektywnej!

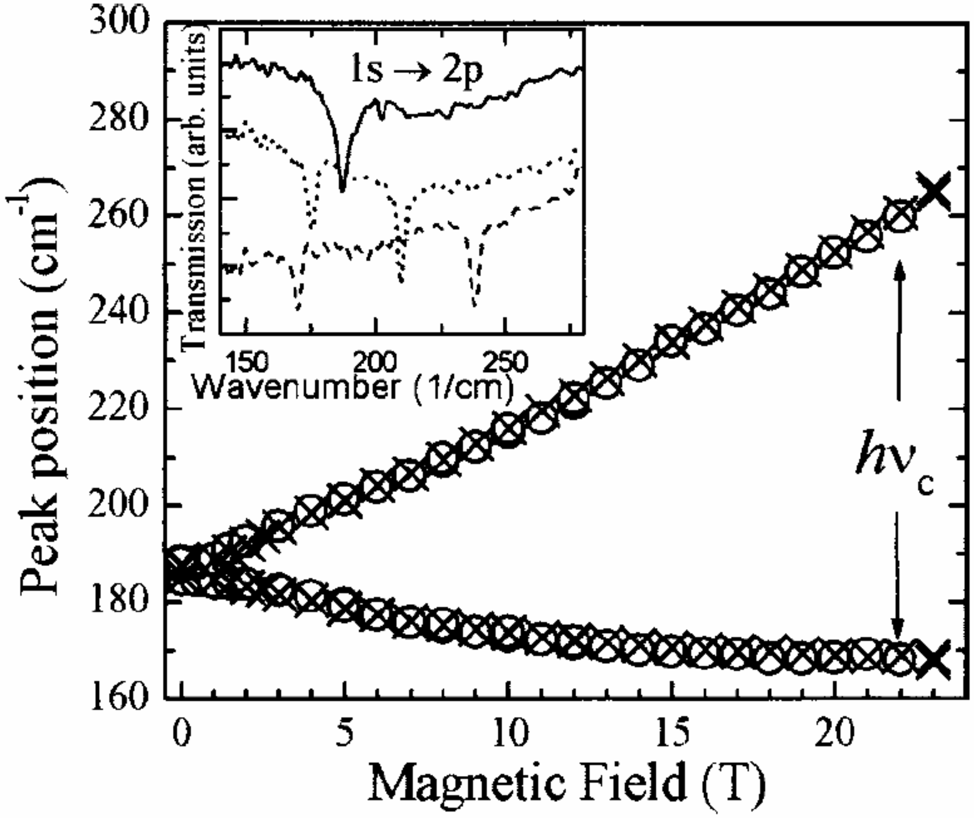
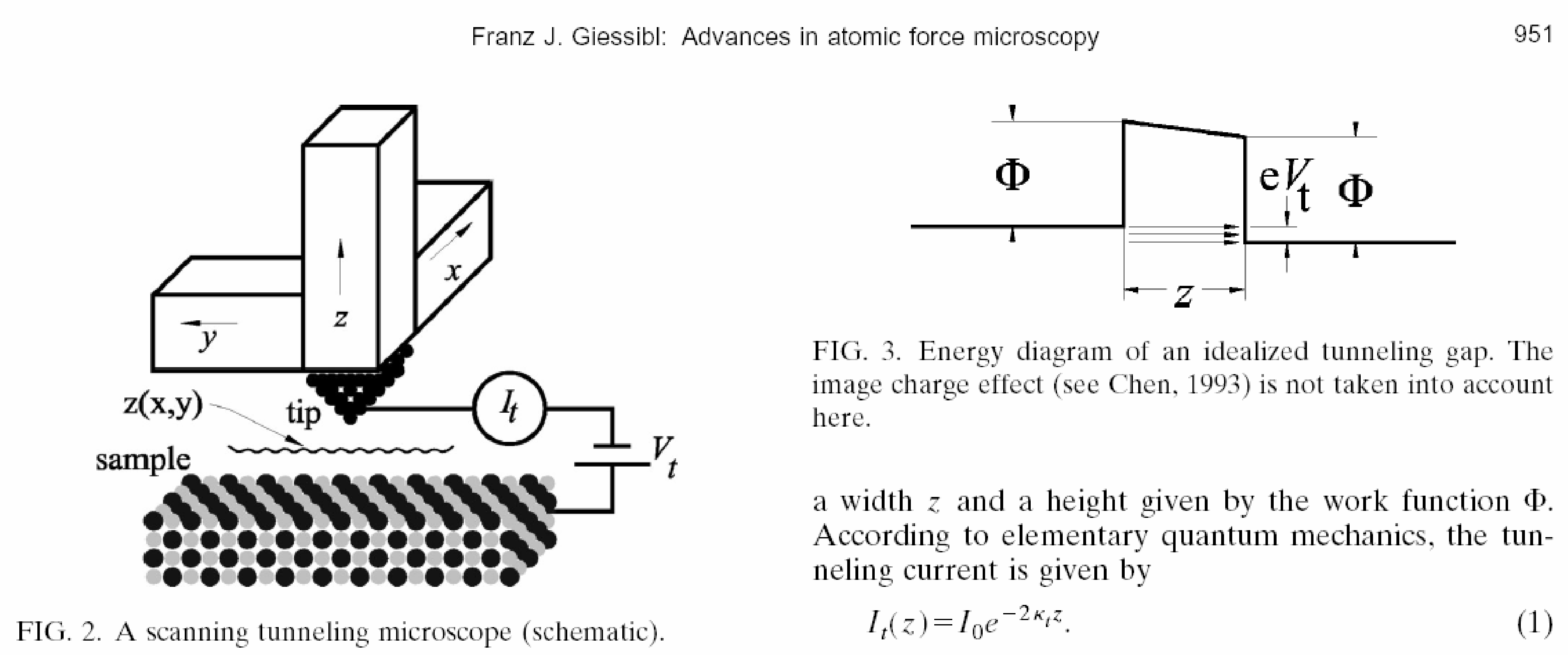


FIG. 1. Positions of $1s \rightarrow 2p_-$ (lower set of points) and $1s \rightarrow 2p_+$ transitions (upper set) vs external magnetic fields measured at 4.5 K. Crosses (circles) denote data for undoped (Si doped) GaN layers grown on sapphire. In the inset transmission of the doped sample normalized by the transmission of a sapphire slab is presented measured at 0 (solid line), 8 (dotted line), and 16 T (dashed line).

$m^* = 0.222(2)\ m_0$

A. M. Witowski, K. Pakuła, J. M. Baranowski, M. L. Sadowski and P. Wyder,
APL 75, 4154 (1999)

Zobaczyć funkcję falową donora – np. przy użyciu mikroskopu tunelowego



Franz J. Giessibl: Advances in atomic force microscopy 951

FIG. 2. A scanning tunneling microscope (schematic).

FIG. 3. Energy diagram of an idealized tunneling gap. The image charge effect (see Chen, 1993) is not taken into account here.

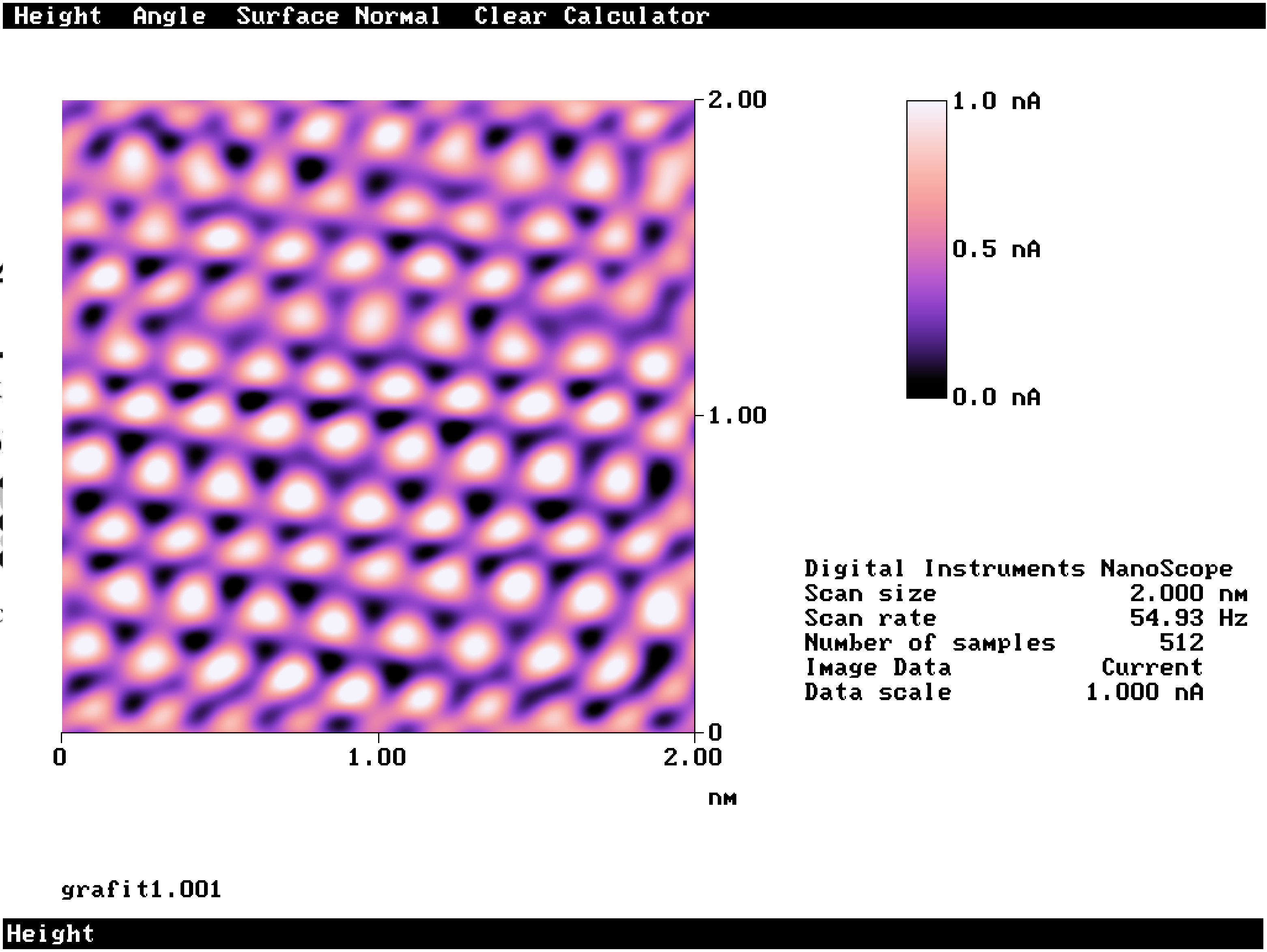
a width z and a height given by the work function Φ. According to elementary quantum mechanics, the tunneling current is given by

$$I_t(z)=I_0e^{-2\kappa_t z}. \quad (1)$$

STM

951

FIG. 2. A sc



```
Digital Instruments NanoScope
Scan size              2.000 nm
Scan rate              54.93 Hz
Number of samples        512
Image Data            Current
Data scale            1.000 nA
```

grafit1.001

gap. The
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(1)

Igły muszą być ostre…

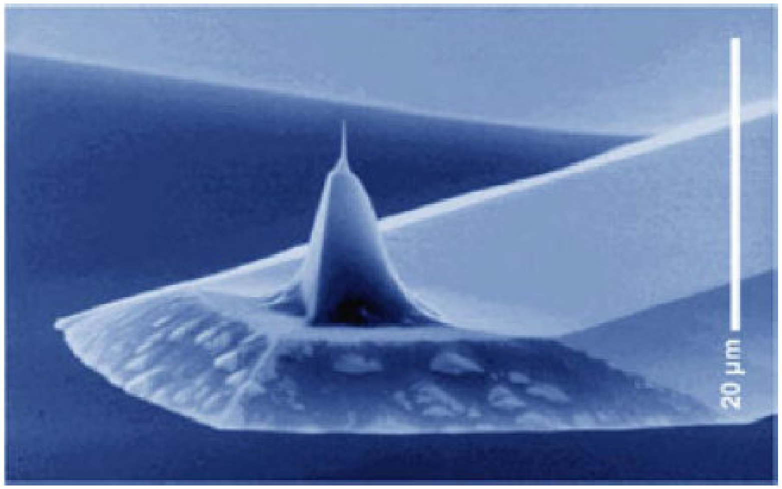

FIG. 8. (Color in online edition) Scanning electron micrograph of a micromachined silicon cantilever with an integrated tip pointing in the [001] crystal direction (Wolter *et al.*, 1991). This is a Pointprobe sensor made by Nanosensors GmbH und Co. KG, Norderfriedrichskoog, Germany D-25870. Photo courtesy of Nanosensors GmbH & Co. KG.

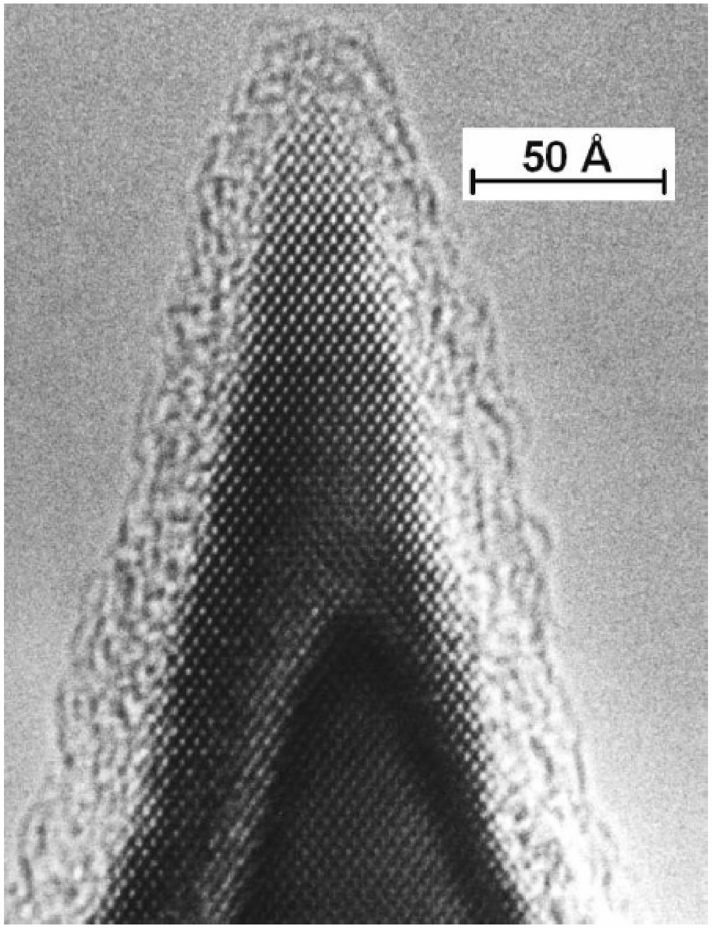

FIG. 13. Transmission electron micrograph of an extremely sharp silicon tip. The native oxide has been etched away with hydrofluoric acid before imaging. The 15–20-Å-thick coating of the tip is mostly due to hydrocarbons which have been polymerized by the electron beam. Interestingly, the crystal structure appears to remain bulklike up to the apex of the tip. From Marcus *et al.*, 1990.

Scanning Tunneling Microscopy Studies of Si Donors ($\mathrm{Si}_{\mathrm{Ga}}$) in GaAs

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We report scanning tunneling microscopy (STM) studies of Si substitutional donors ($\mathrm{Si}_{\mathrm{Ga}}$) in GaAs that reveal delocalized and localized electronic features corresponding to $\mathrm{Si}_{\mathrm{Ga}}$ in the top few layers of the (110) cleavage surface. The delocalized features appear as protrusions a few nm in size, superimposed on the background lattice. These features are attributed to enhanced tunneling due to the local perturbation of the band bending by the Coulomb potential of subsurface $\mathrm{Si}_{\mathrm{Ga}}$. In contrast, STM images of surface $\mathrm{Si}_{\mathrm{Ga}}$ show very localized electronic structures, in good agreement with a recent theoretical prediction [J. Wang *et al.*, Phys. Rev. B **47**, 10 329 (1993)].

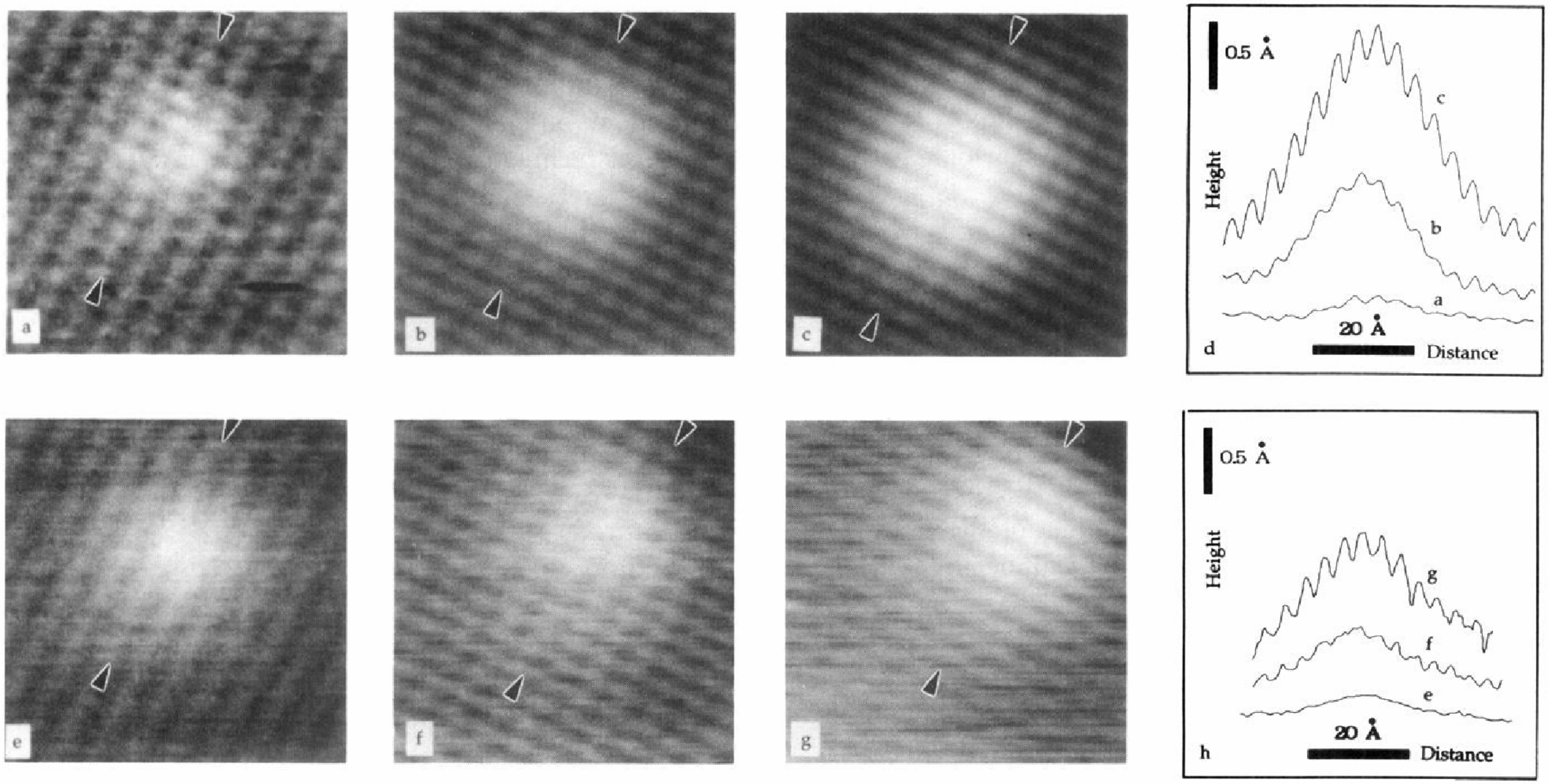
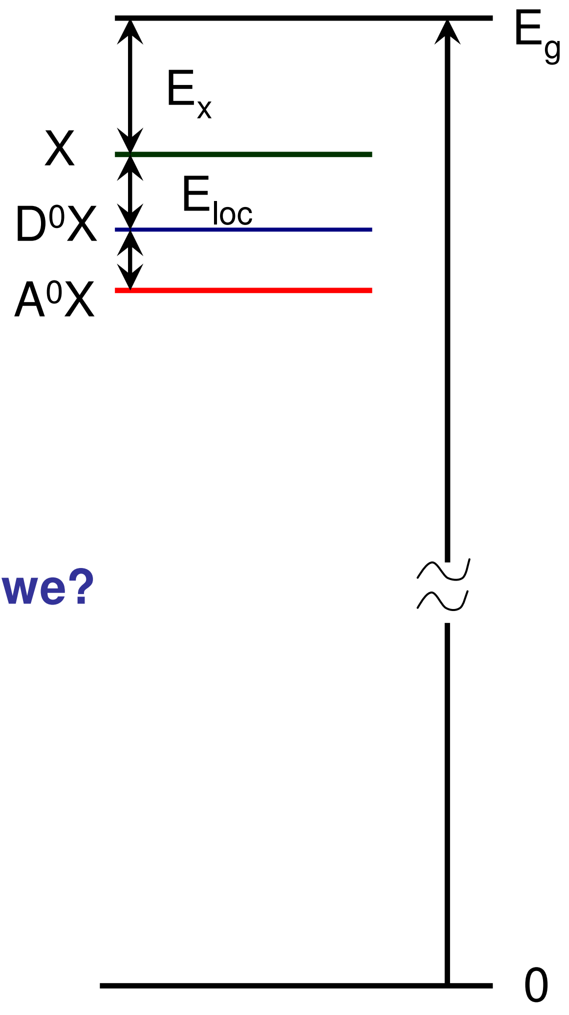


FIG. 3. STM images of the protrusion region *D* in Fig. 1 taken with tunneling current of 0.5 nA at various sample voltages. The sample voltages are (a) −3 V; (b) −2.0 V, (c) −1.5 V; (e) +3.0 V; (f) +2.0 V; and (g) +1.5 V. The topographic profiles along the $[1\bar{1}0]$ direction (indicated by the arrows) across the features are shown in (d) and (h). All images are 60 Å × 60 Å in size.

Przegląd kompleksów ekscytonowych

Ekscyton zwiazany

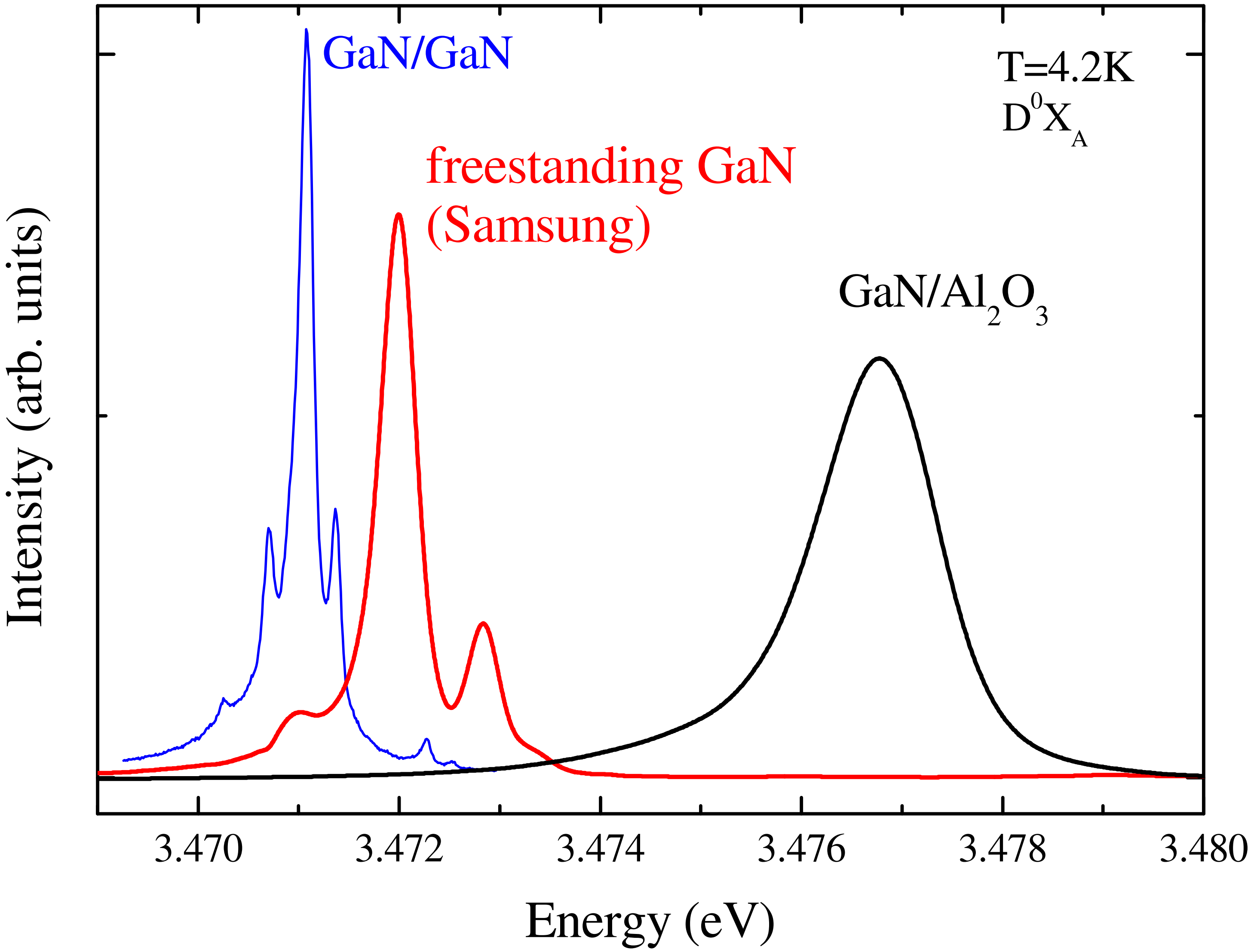
- na neutralnym donorze D^0X
- na neutralnym akceptorze A^0X
- na zjonizowanym donorze D^+X
- na zjonizowanym akceptorze A^-X



Jak zidentyfikować poszczególne linie ekscytonowe?

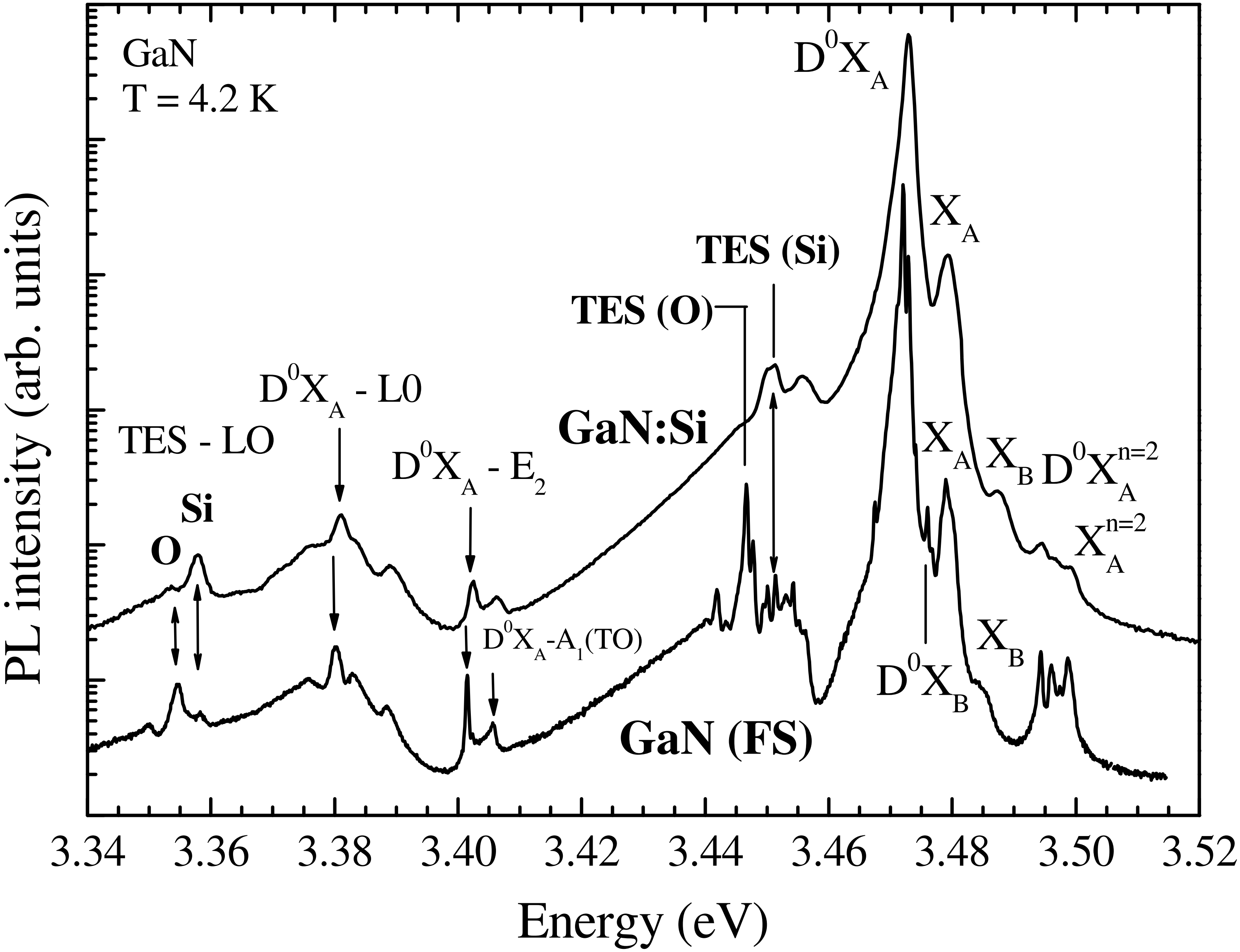
Nie jest to łatwe!

Luminescencja ekscytonowa w GaN

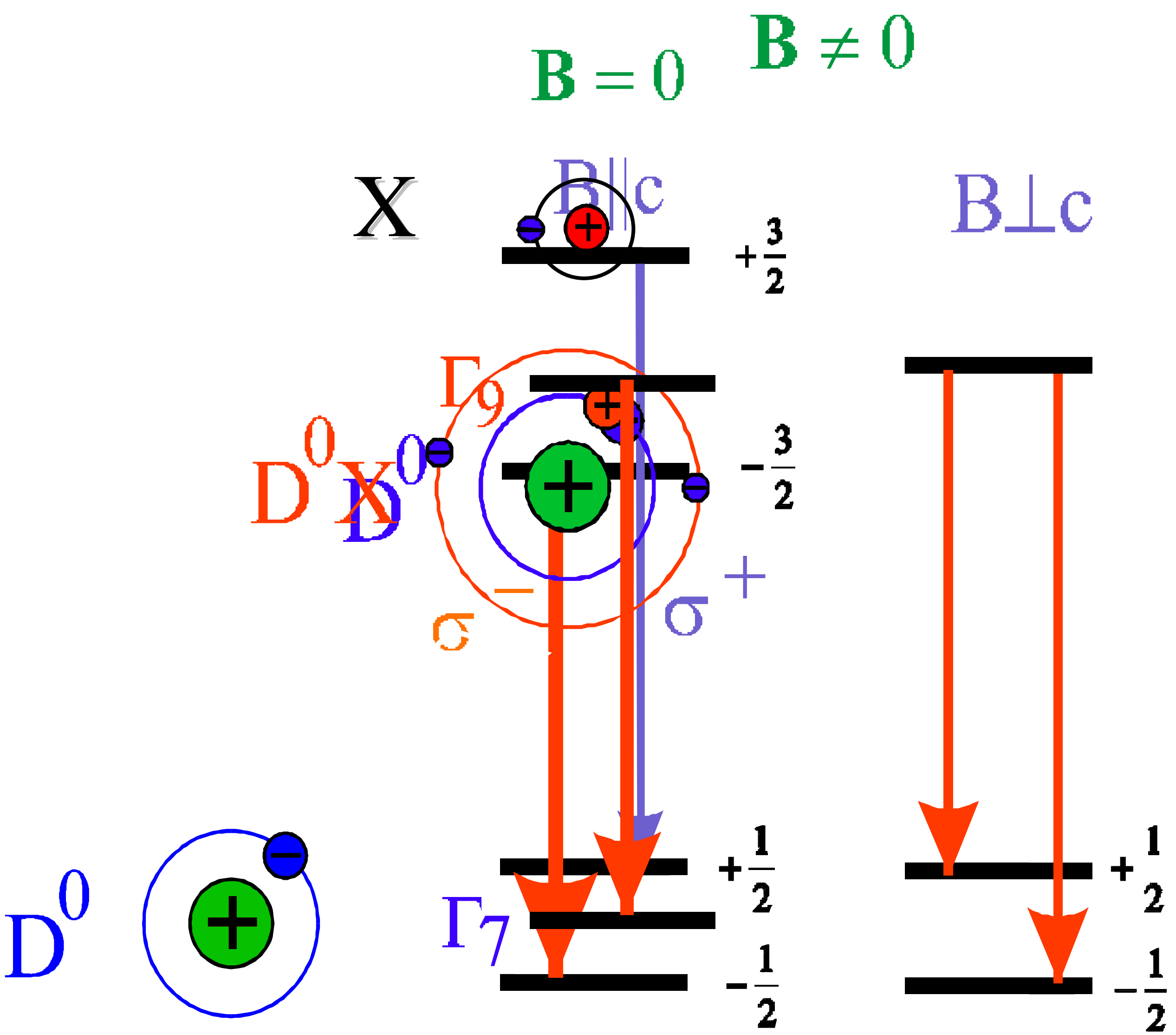


A. Wysmolek et al. PRB 74, 195205 (2006)

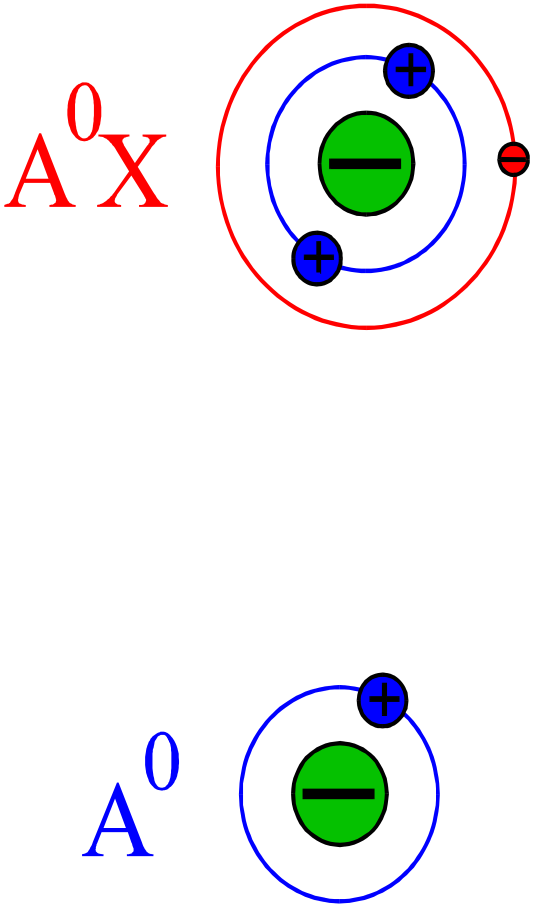
Donor tlenowy donor krzemowy

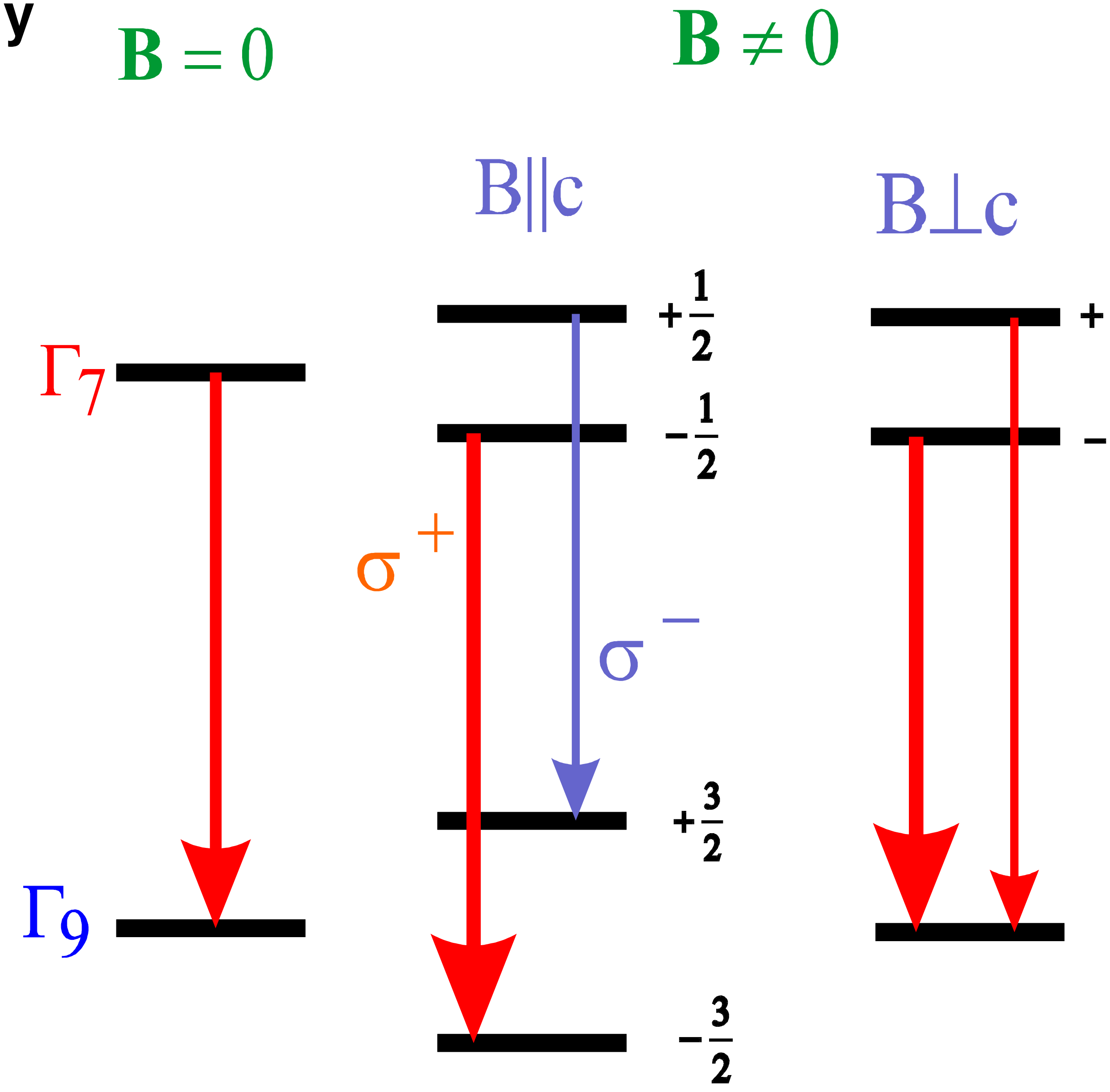


Ekscyton związany na neutralnym donorze (D^0X)

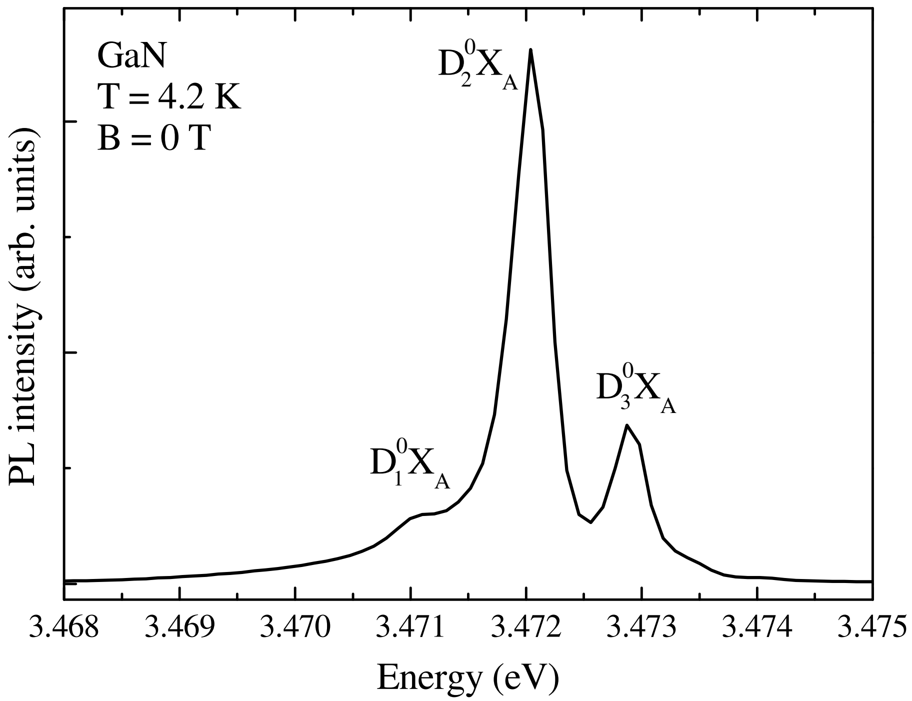


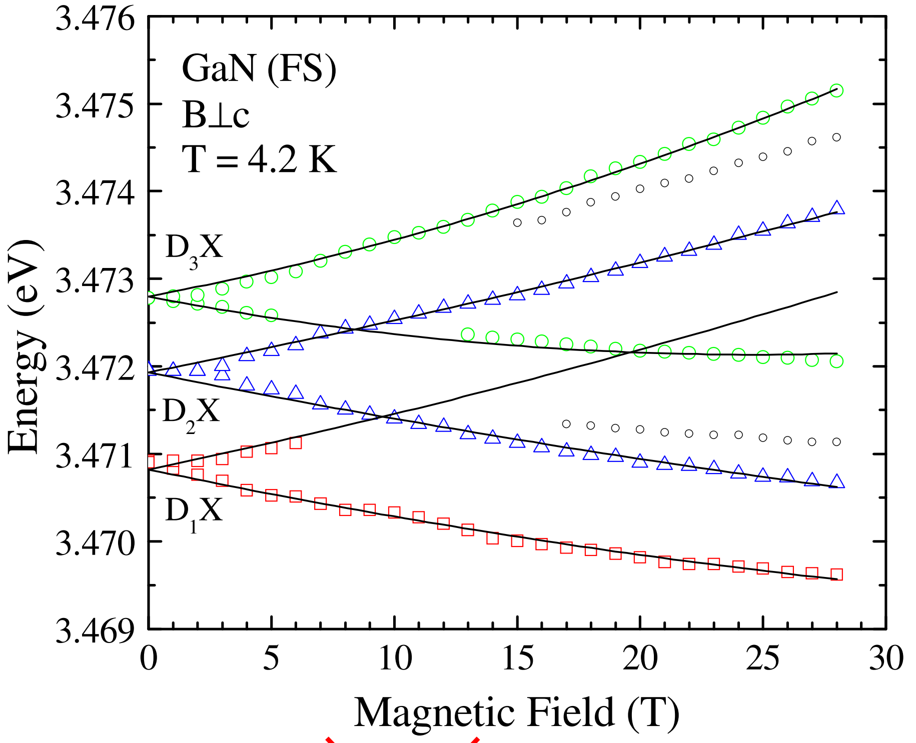
Ekscyton związany na neutralnym akceptorze





Rozszczepienia spinowe – konfiguracja B⊥c





$D_1{}^0X_A$ – O_N

$D_2{}^0X_A$ – Si_{Ga}

$D_3{}^0X_A$ – ?(V_N)

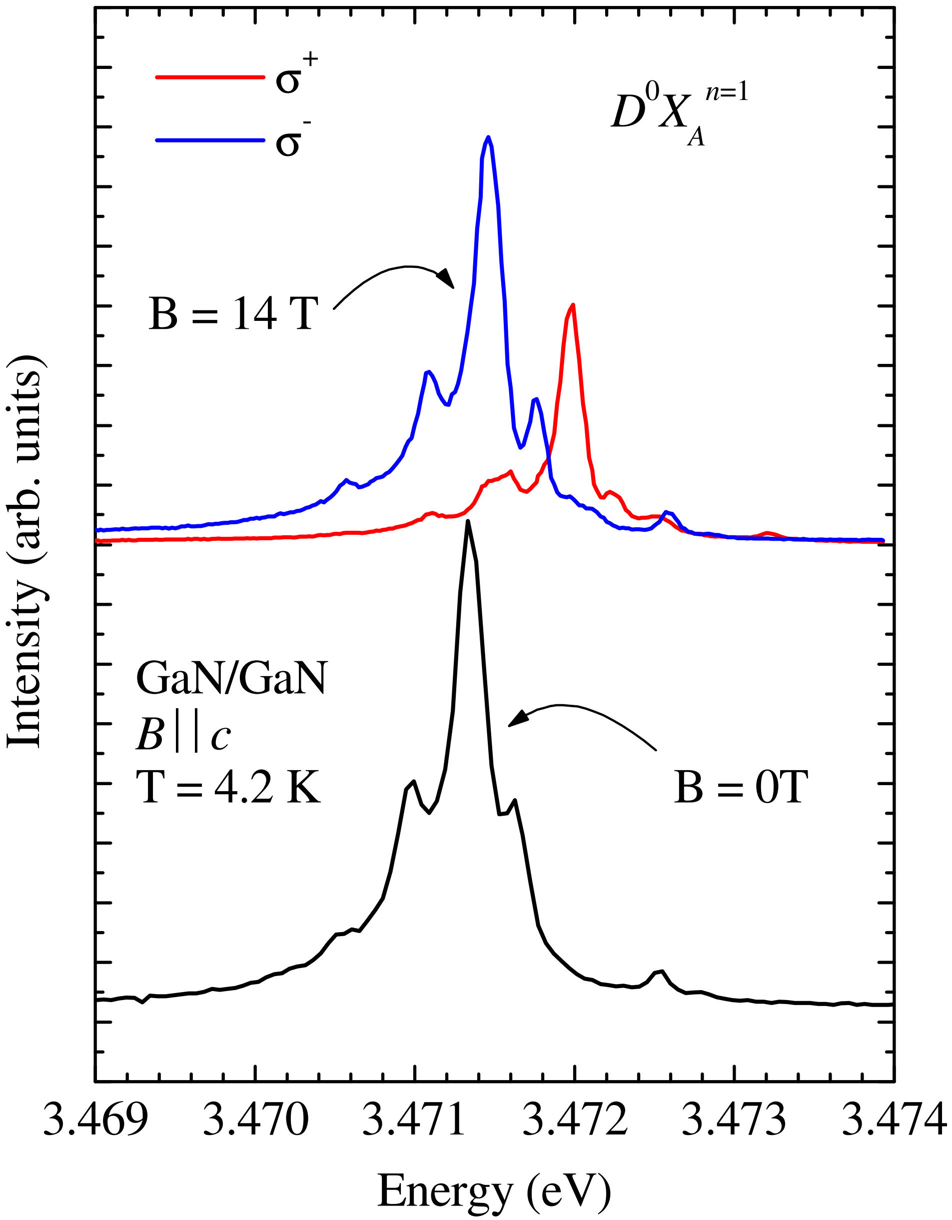
$D_1{}^0X_A$ – ~~D^+X~~

$D_2{}^0X_A$ – O_N

$D_3{}^0X_A$ – Si_{Ga}

Wysmolek et al. PRB 66, 245317 (2002)

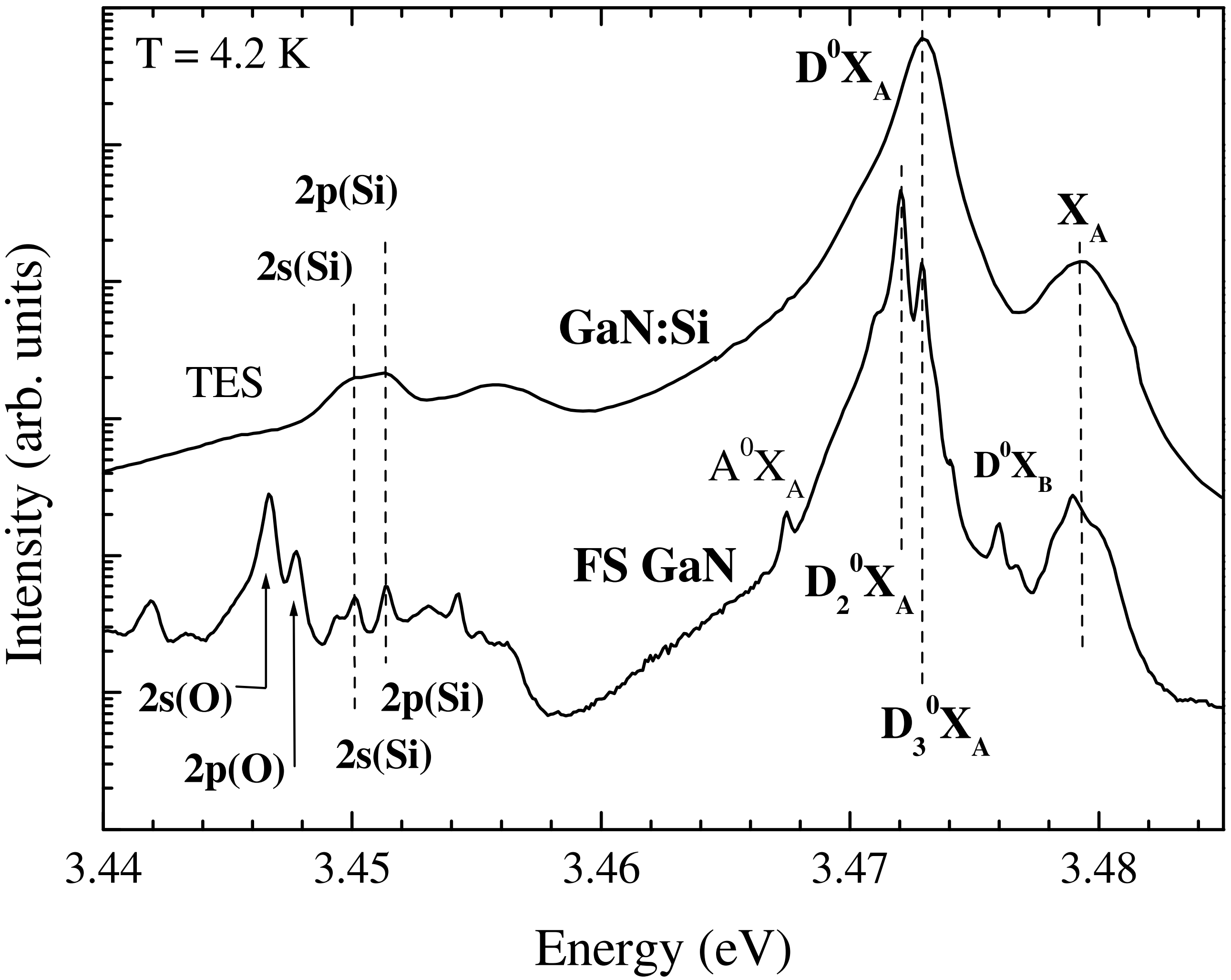
A. Freitas, Jr., PRB **66**, 233311 (2002).



Konfiguracja B || c

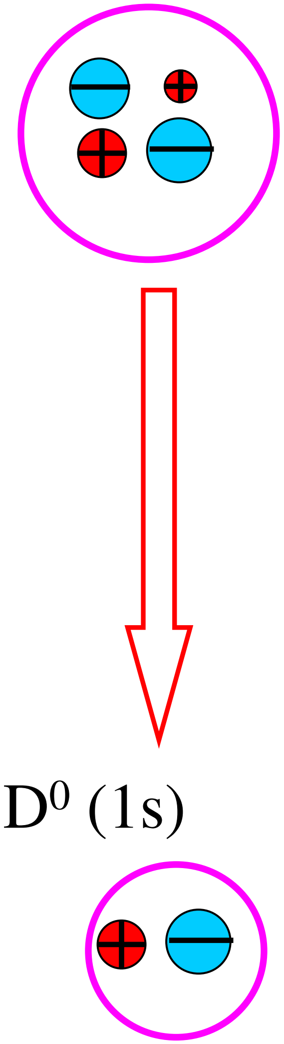
Zachowanie typowe dla D^0X!

Rozróżniamy donory o różnych energiach wiązania…

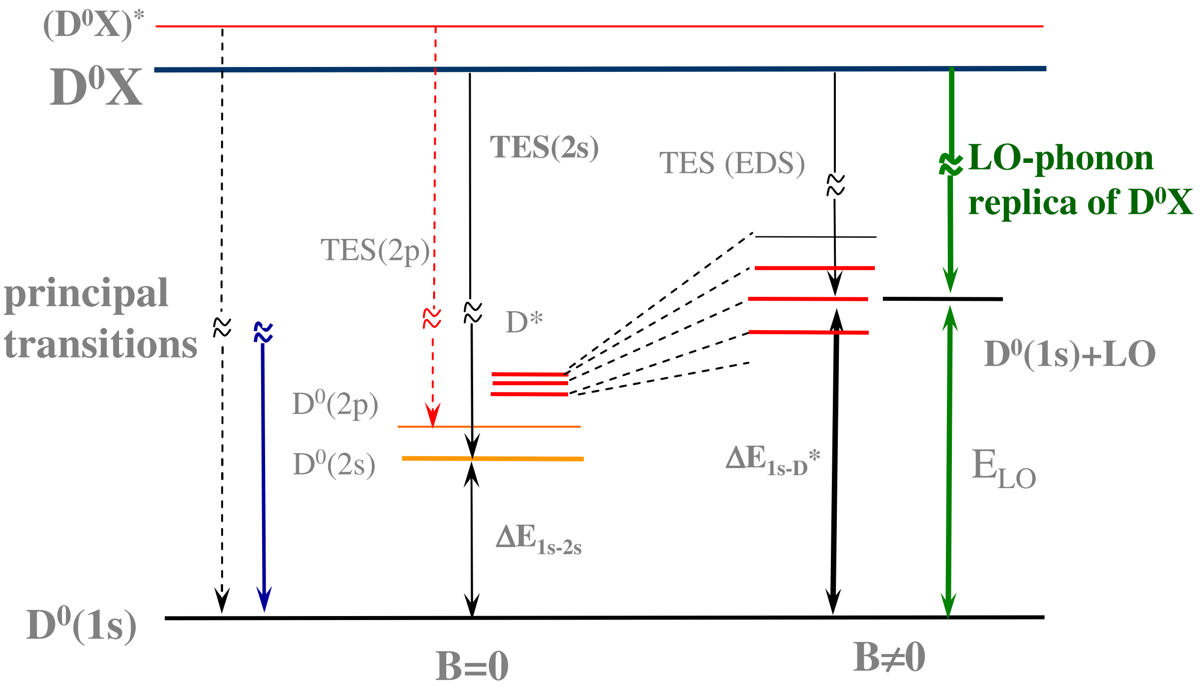


Different recombination channels of D^0X

D^0X



D^0 (1s)



$(D^0X)^*$

D^0X

principal transitions

TES(2p)

TES(2s)

D*

$D^0(2p)$

$D^0(2s)$

ΔE_{1s-2s}

TES (EDS)

$\Delta E_{1s\text{-}D^*}$

LO-phonon replica of D^0X

$D^0(1s)$+LO

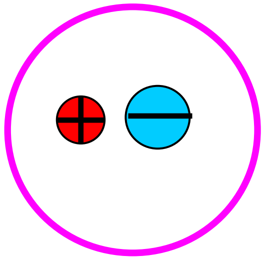
E_{LO}

$D^0(1s)$

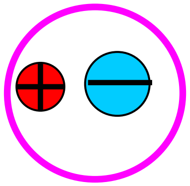
B=0

B≠0

D^0 (2s)

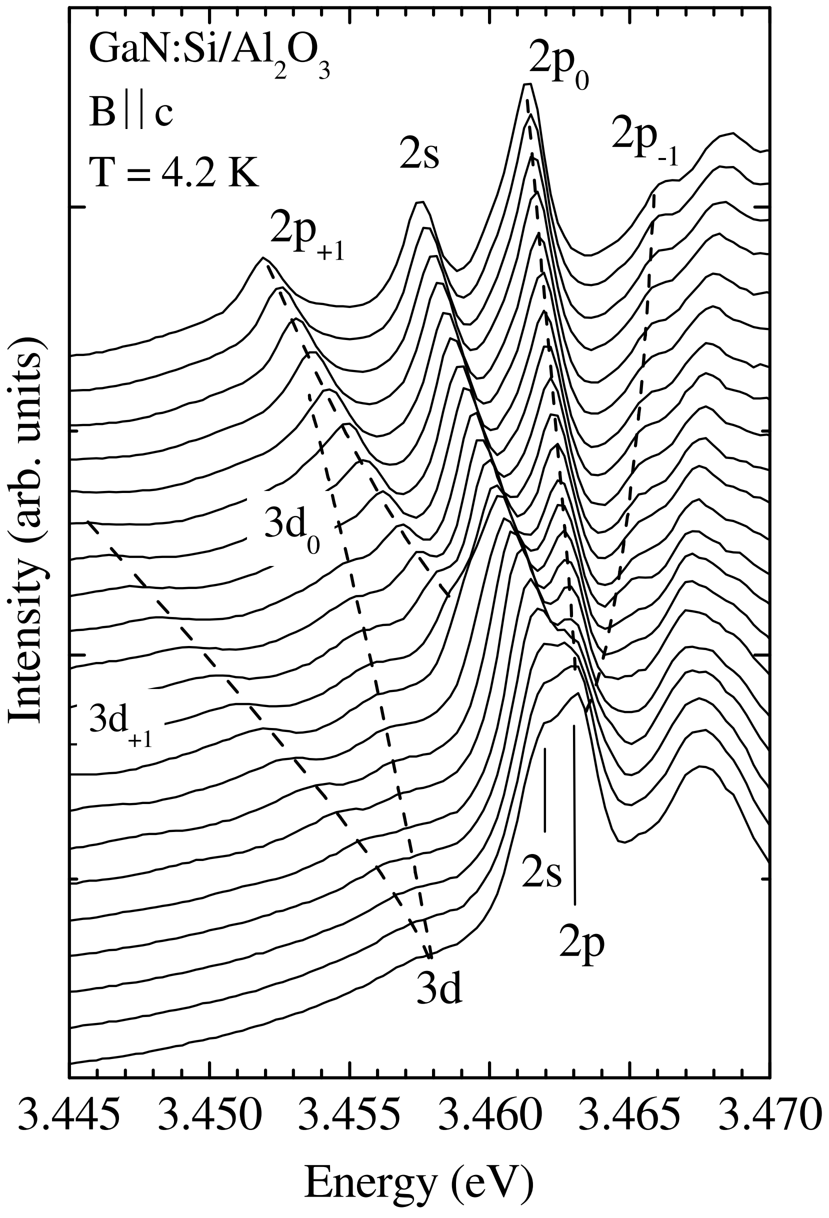


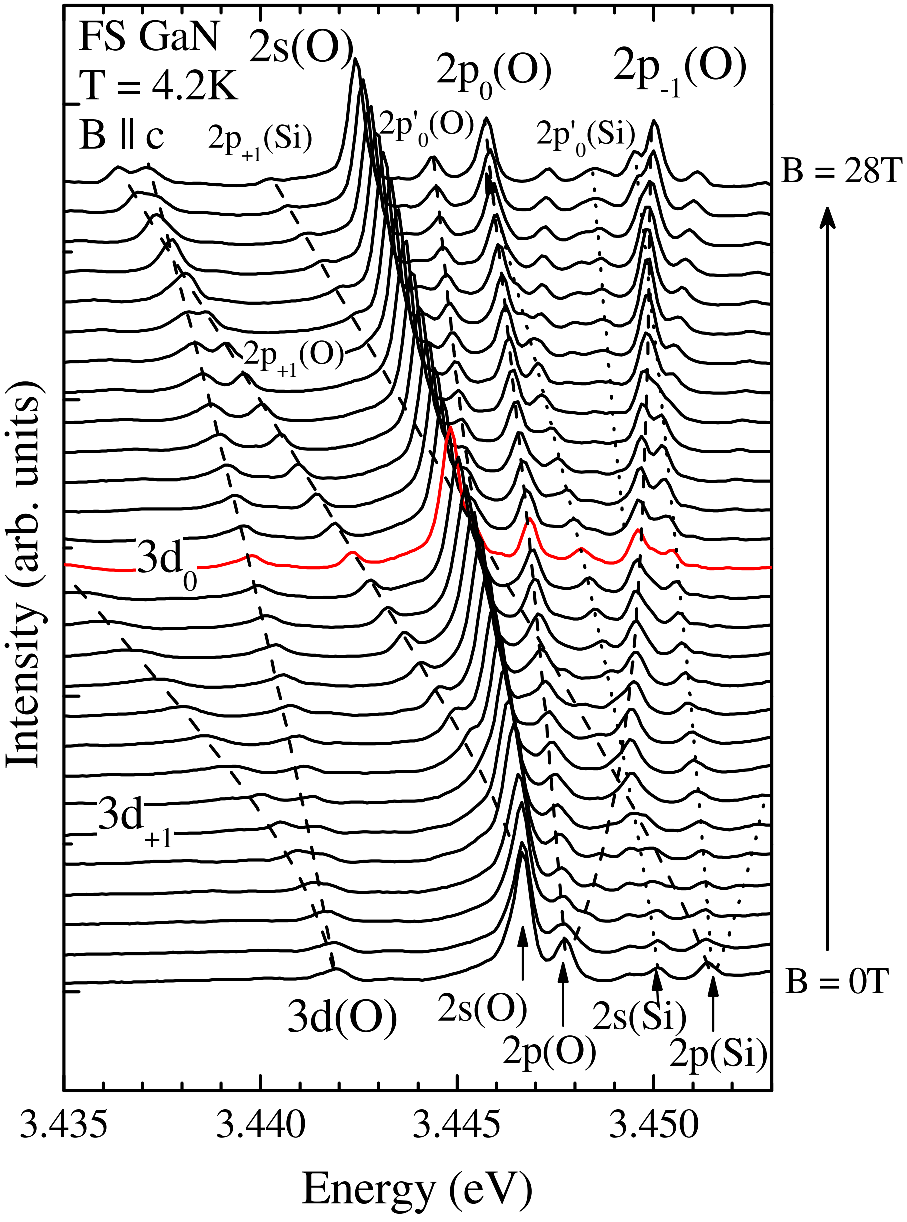
D^0 (1s)



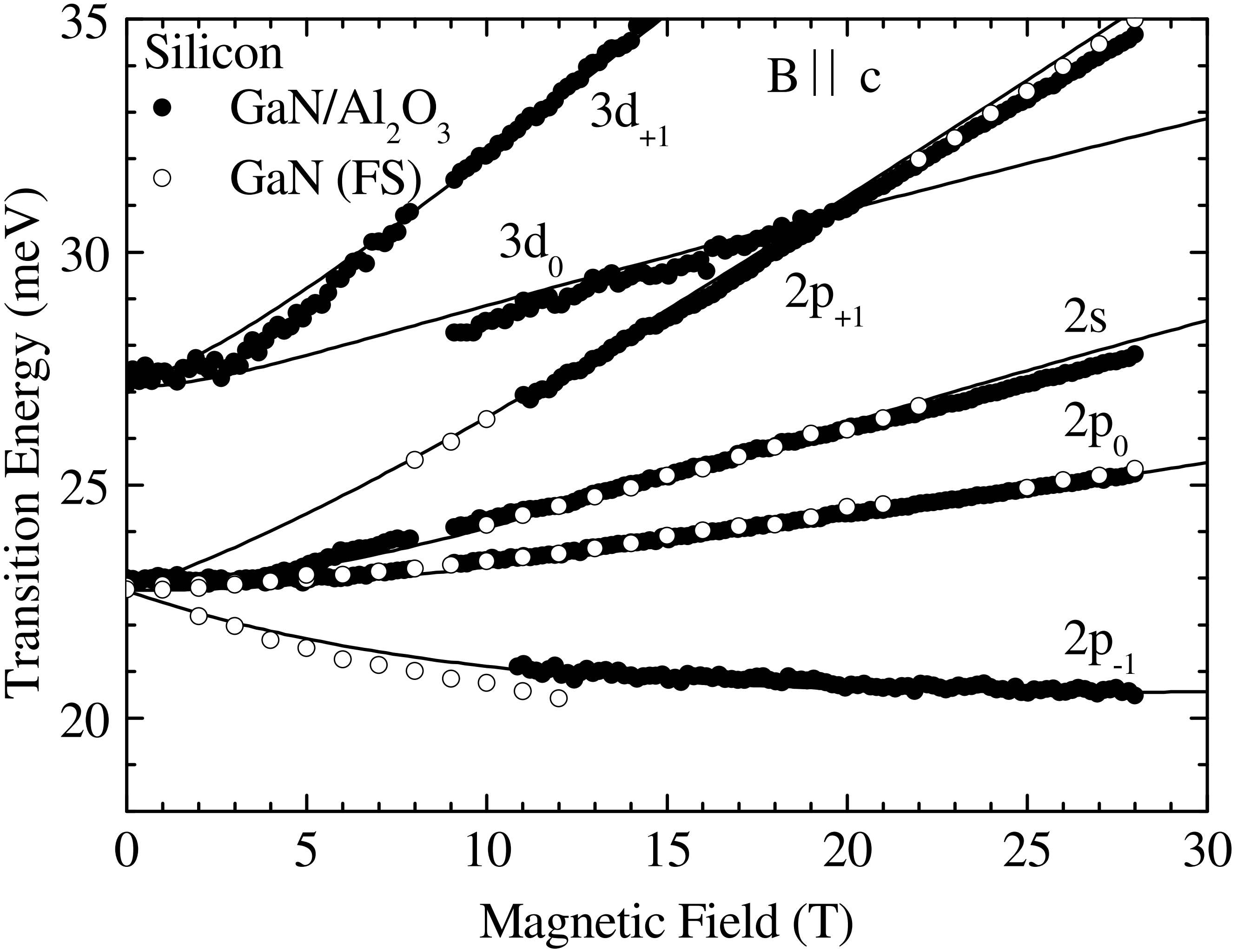
+ LO

Identyfikujemy przejścia używając pola magnetycznego





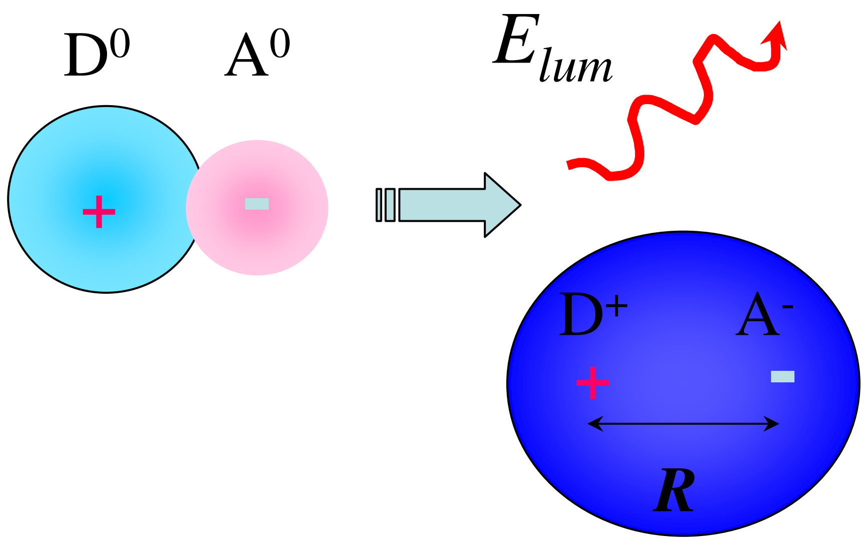
Donor krzemowy

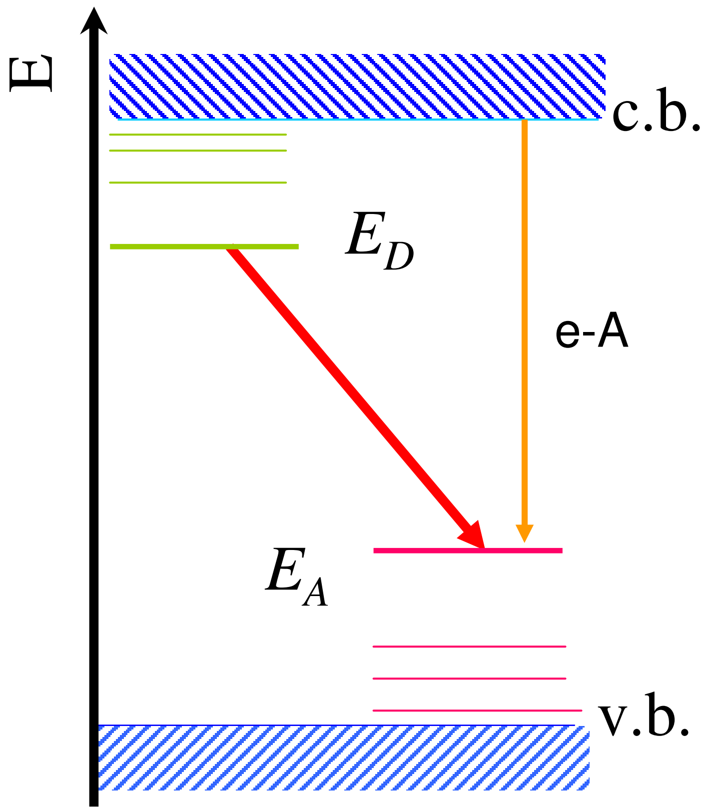


R_y=30.28(5) meV
Δ_{1s}= 0

E_b=30.28meV
m^*=0.214m_0

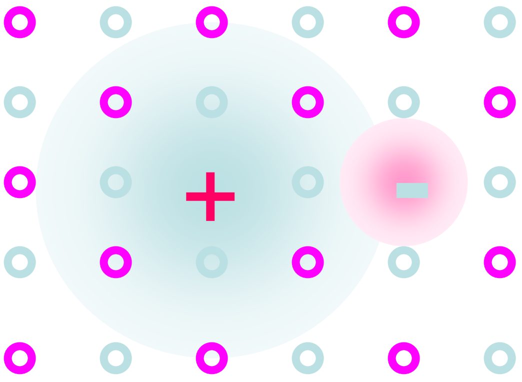
Pary donor-akceptor





$$E_{lum} = E_g - E_A - E_D + e^2/(\varepsilon R)$$

Emisja par donor-akceptor

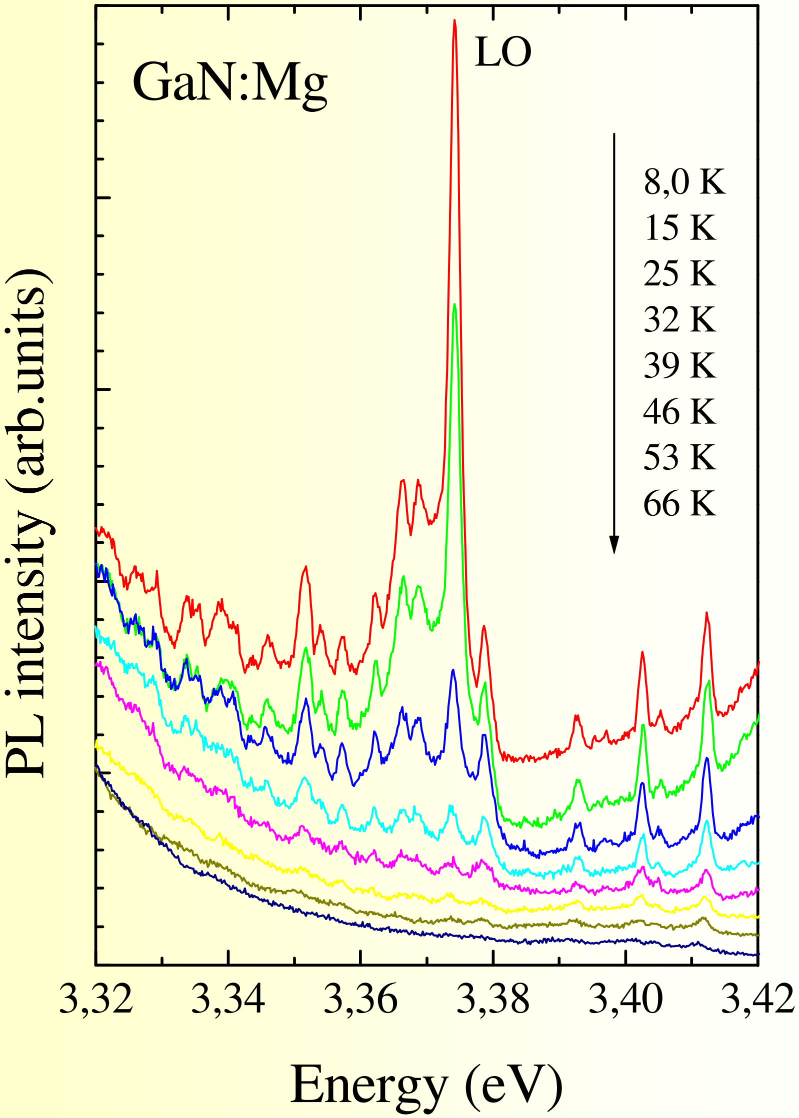


R_n

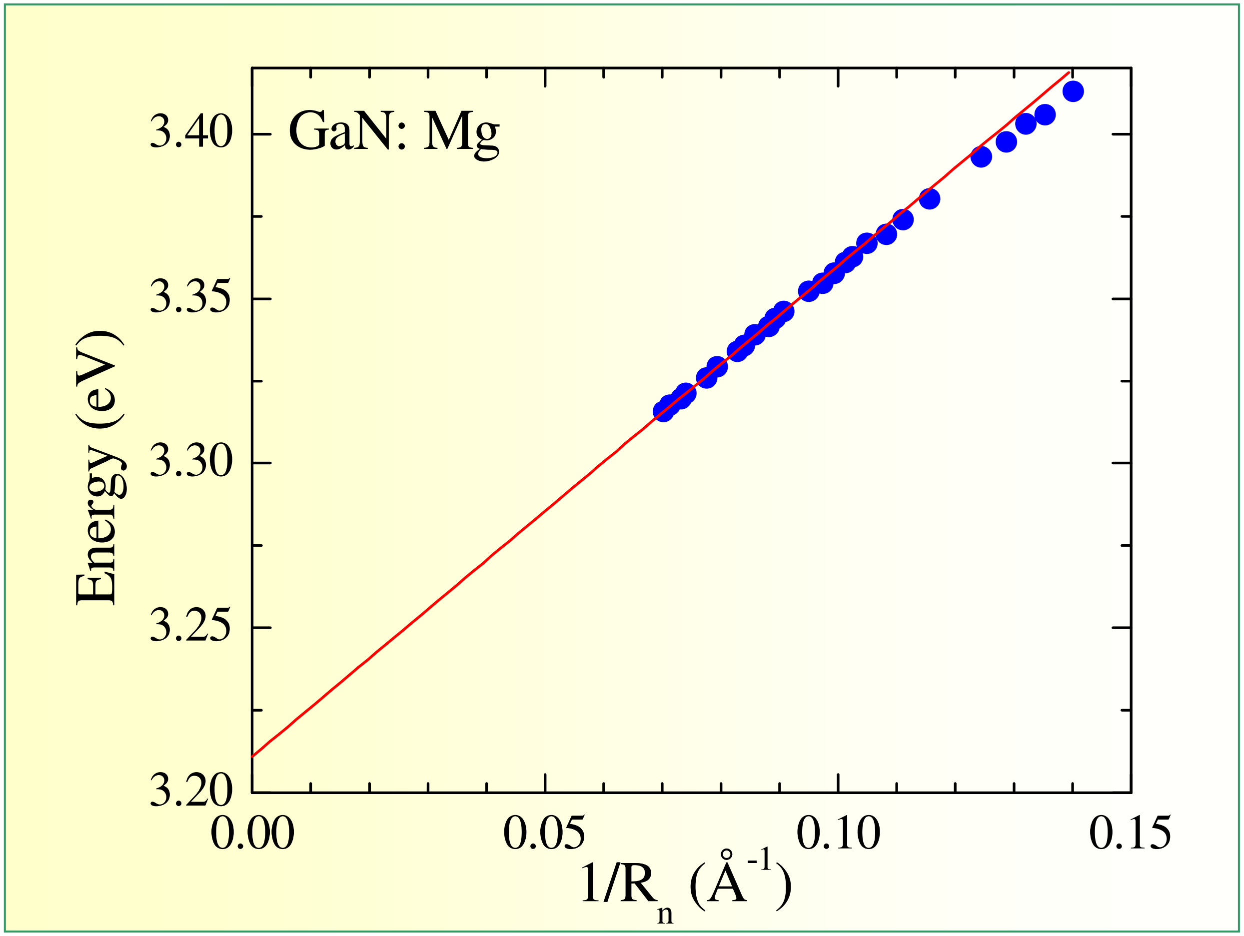
dyskretne odległości D-A

↓

dyskretne linie emisyjne



Emisja par donor-akceptor w GaN



$$E_{lum} = E_g - E_A - E_D + e^2/(4\pi\ \varepsilon_0\varepsilon_s\ R_n) \Rightarrow \boldsymbol{E_D\ ,\ E_{A,}\ \varepsilon_s}$$

„Historyczne” widma par w GaP

A272 THOMAS, GERSHENZON, AND TRUMBORE

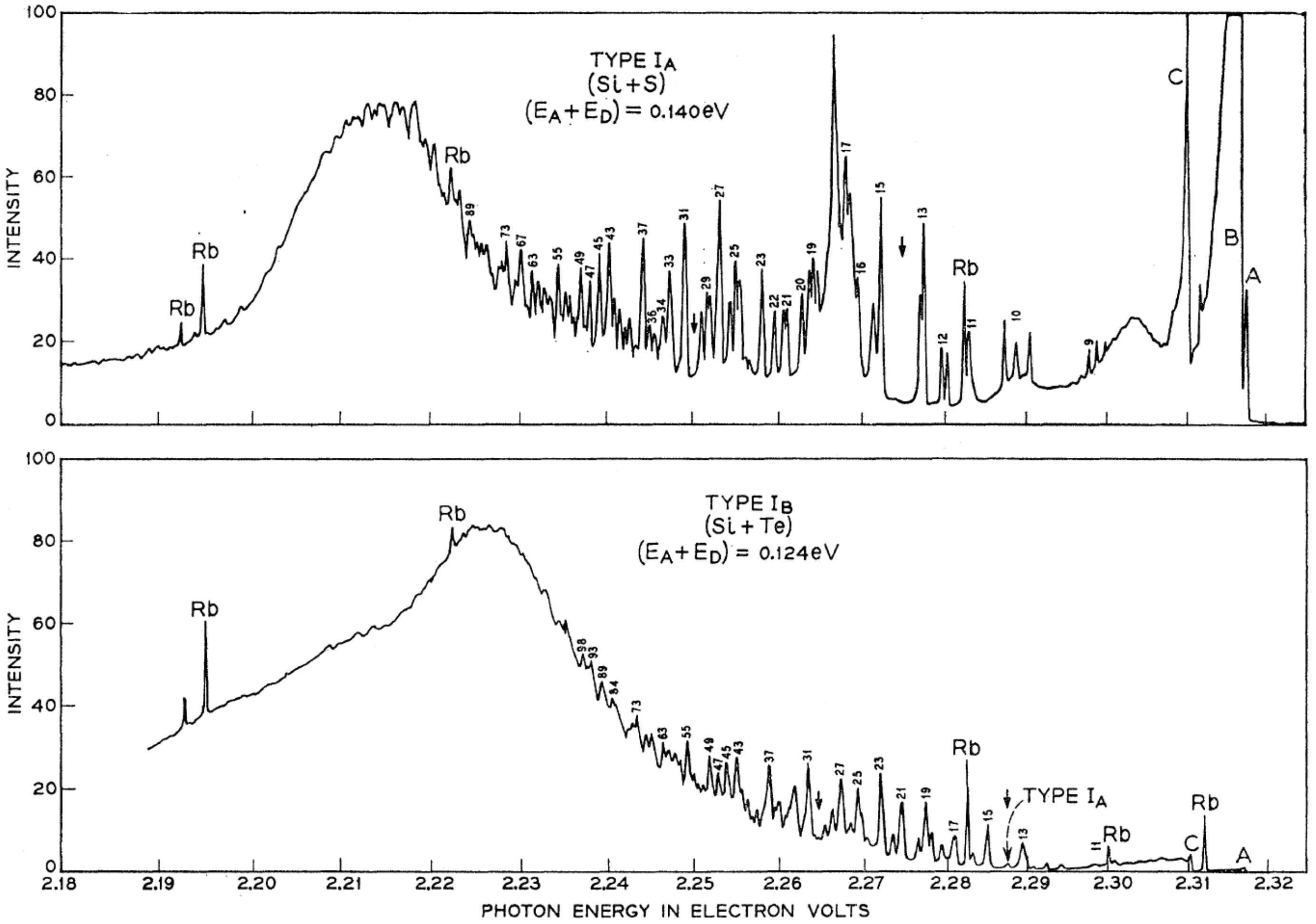
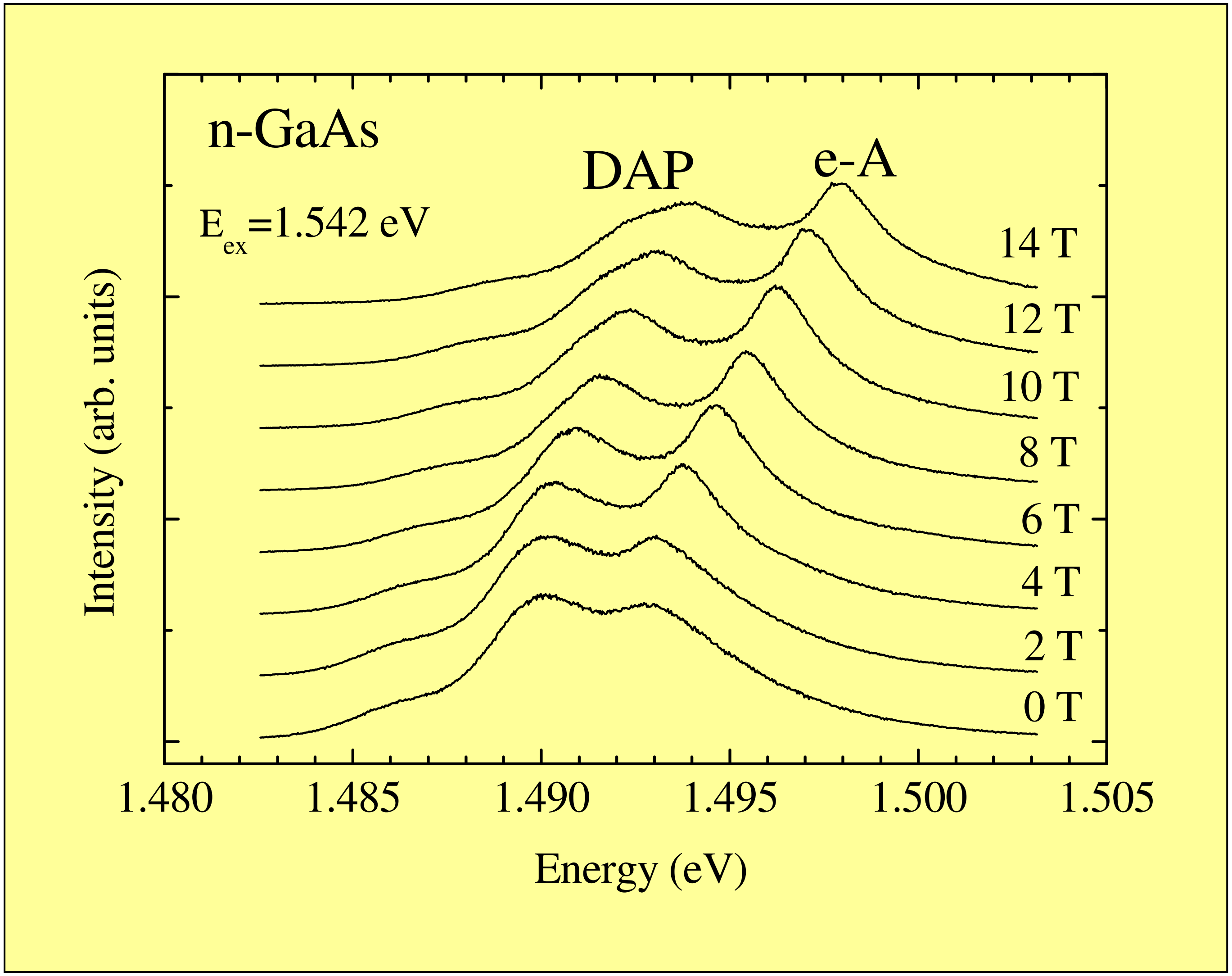


FIG. 2. The photoluminescent spectra (on arbitrary scales) of type I_A and I_B crystals taken at 1.6°K. The lines marked Rb are rubidium calibration lines. The small numbers indicate the shell numbers of the pair spectra. *A*, *B*, and *C* are bound exciton lines. The arrows indicate some positions for which $N(r)=0$, and mark a gap in the spectra. The type I_A crystals are grown without the addition of impurities; the I_B crystals are produced by adding Te.

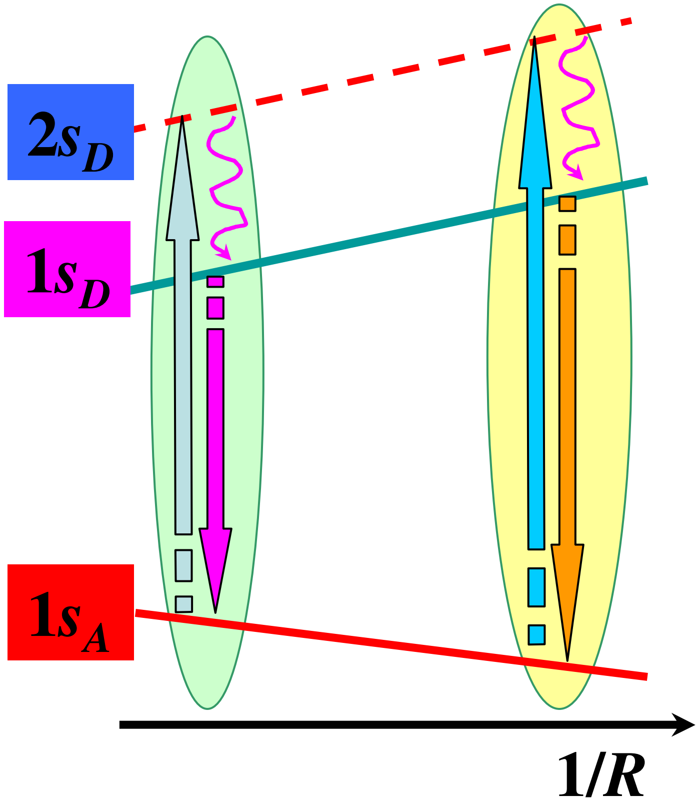
D. G. Thomas et al. Phys. Rev. **133**, A269 (1964)

Luminescencja par donor-akceptor w GaAs

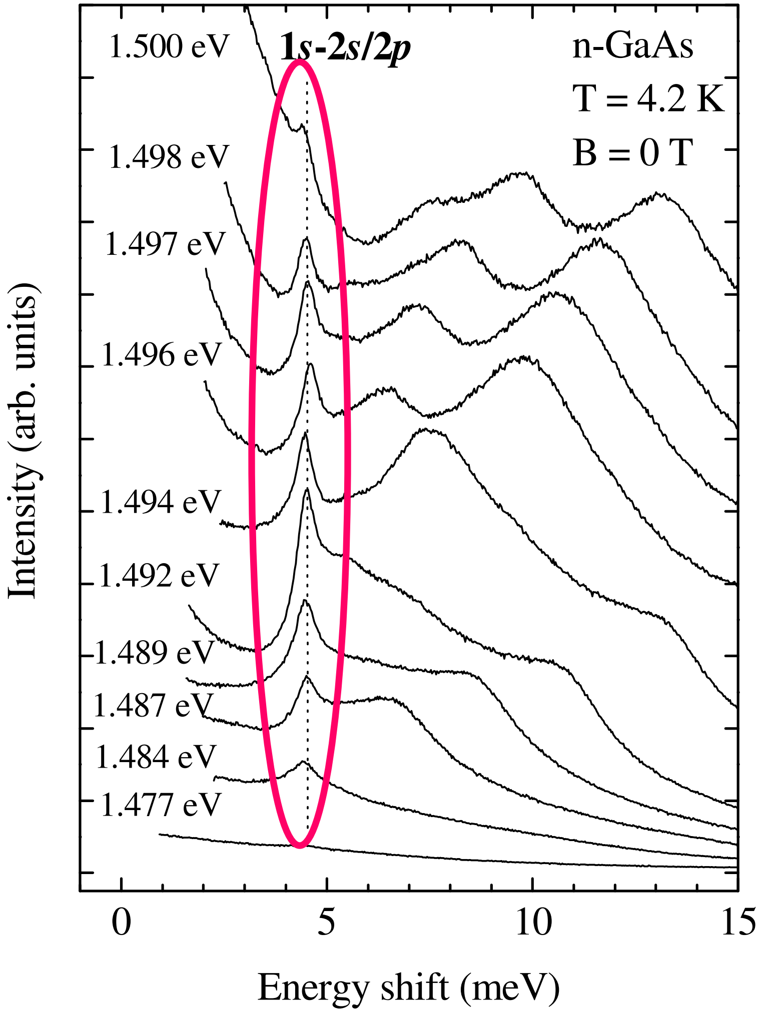
Szerokie linie luminescencyjne! Czy z tego można cos wydobyć?



Selective excitation



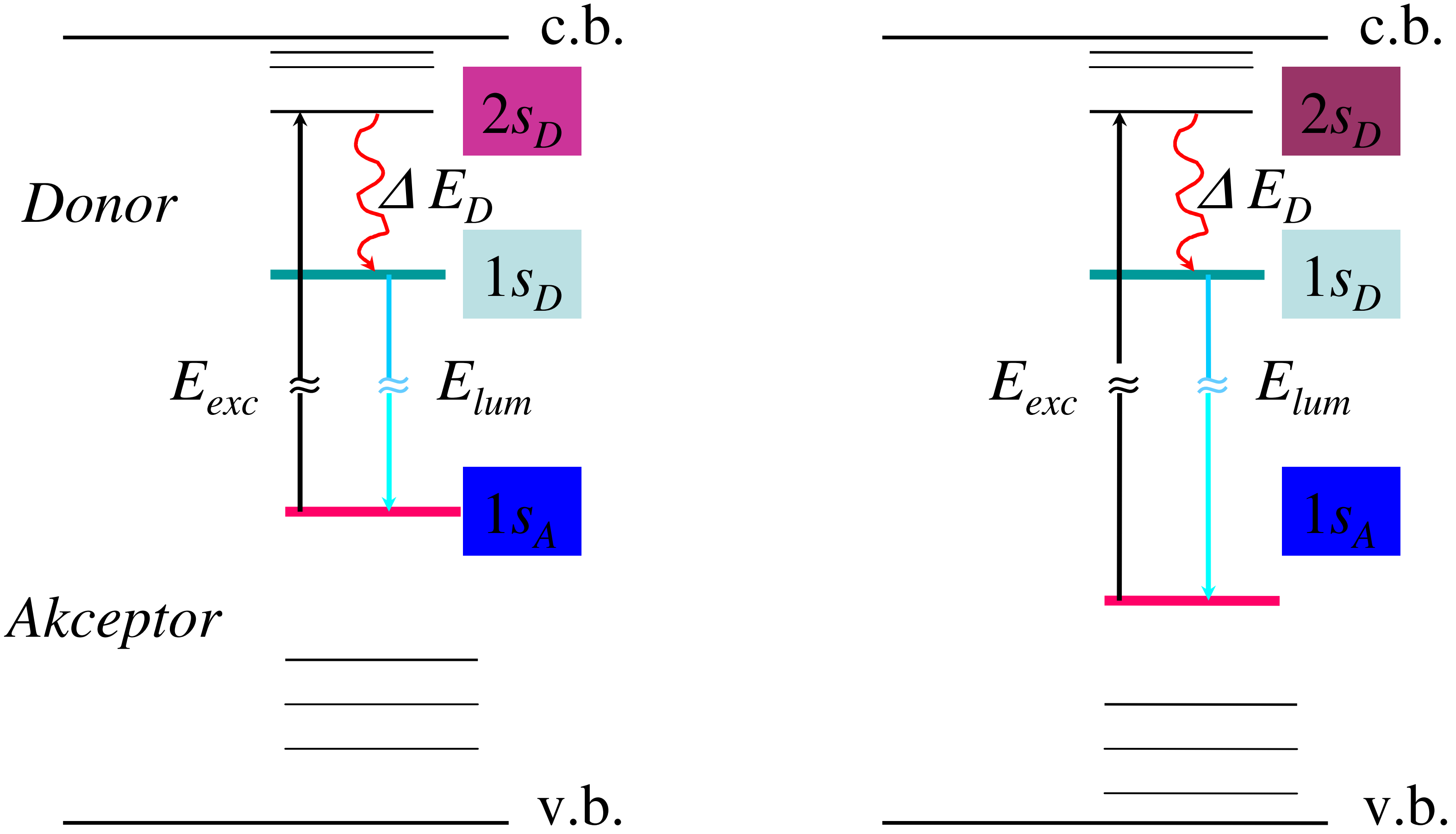
$$E_{exc} - E_{lum} = \Delta E_D$$



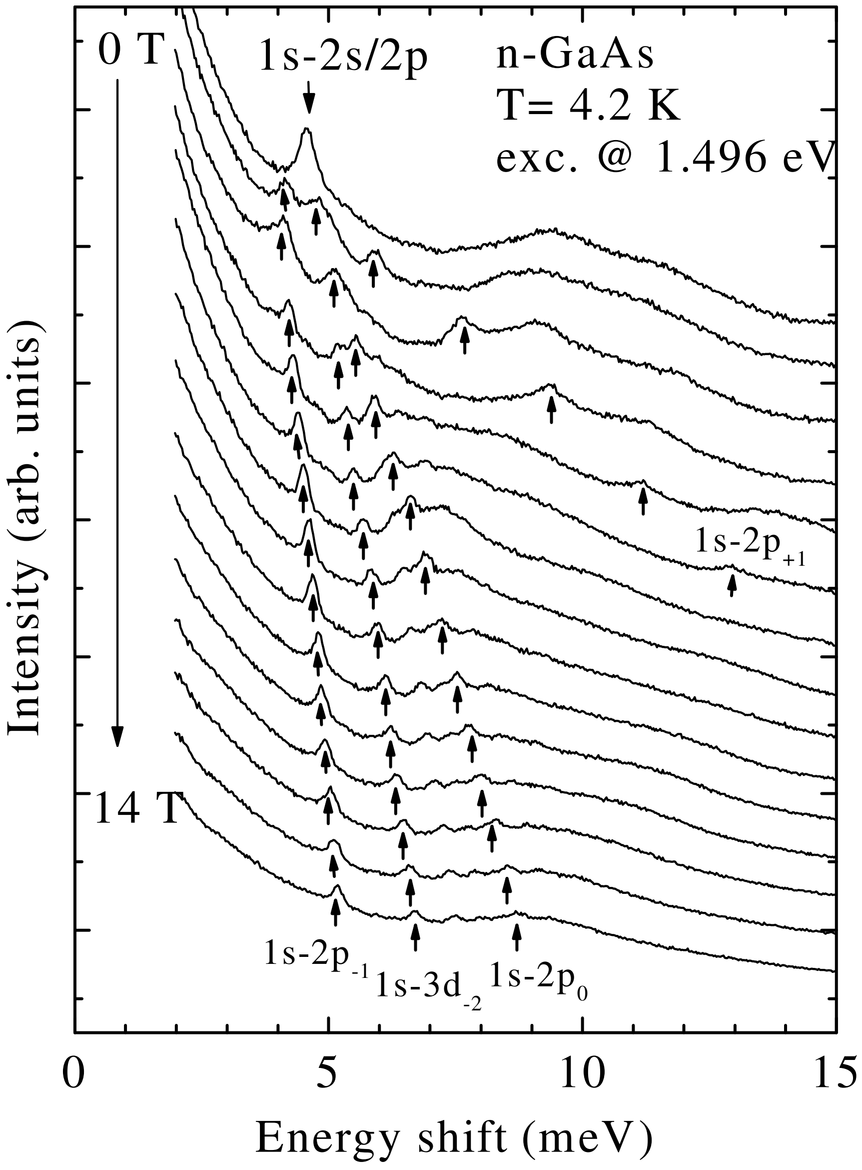
Selektywna spektroskopia par donor-akceptor

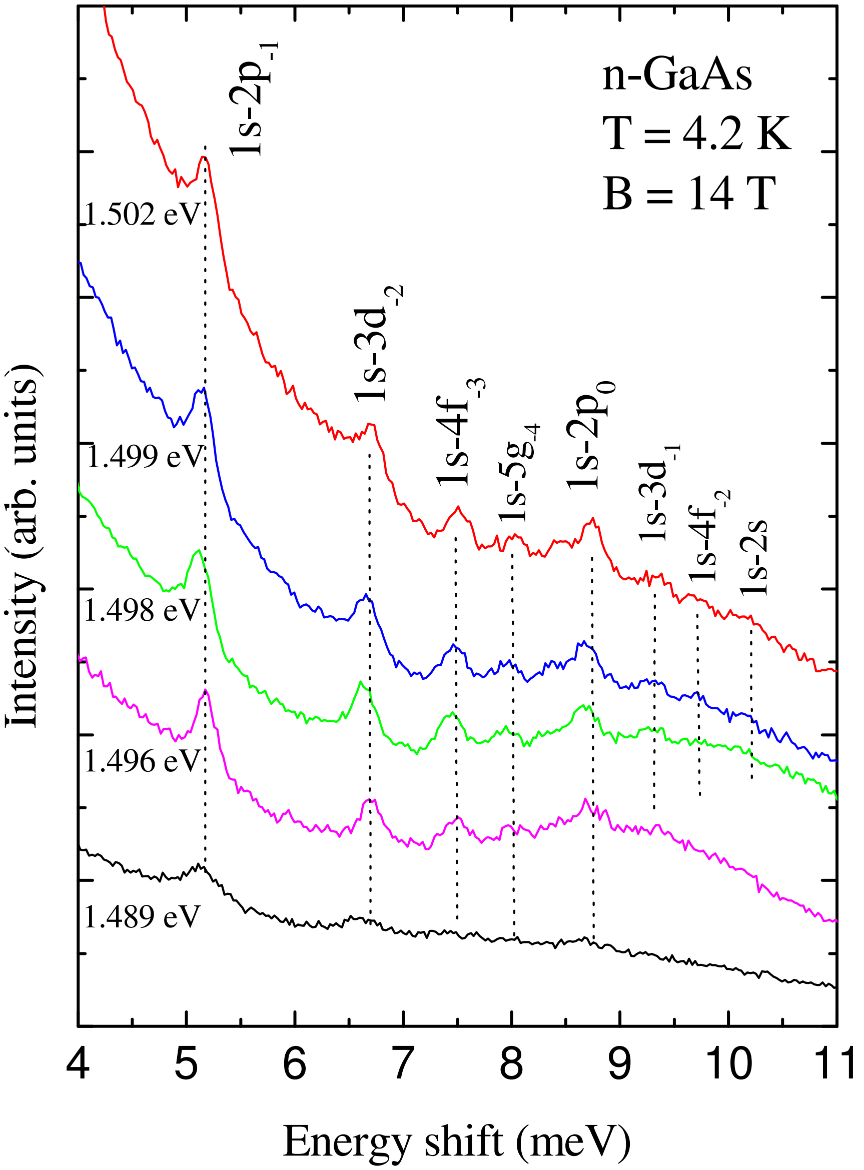
$$E_{lum} = E_g - E_A - E_D + e^2/(4\pi\ \varepsilon_0\varepsilon_s\ R_n)$$

$$R_1 > R_2$$

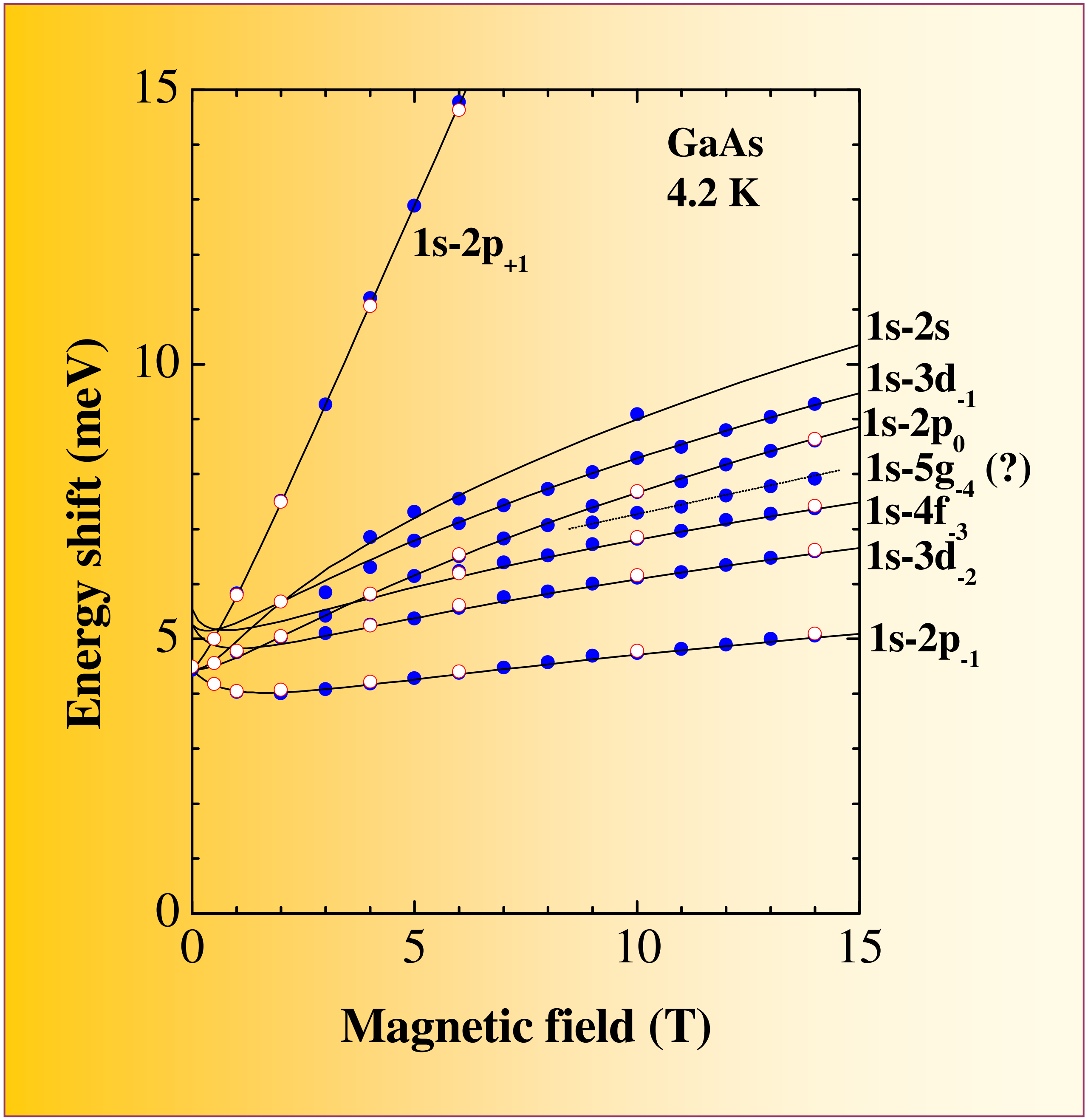


SPL w polu magnetycznym





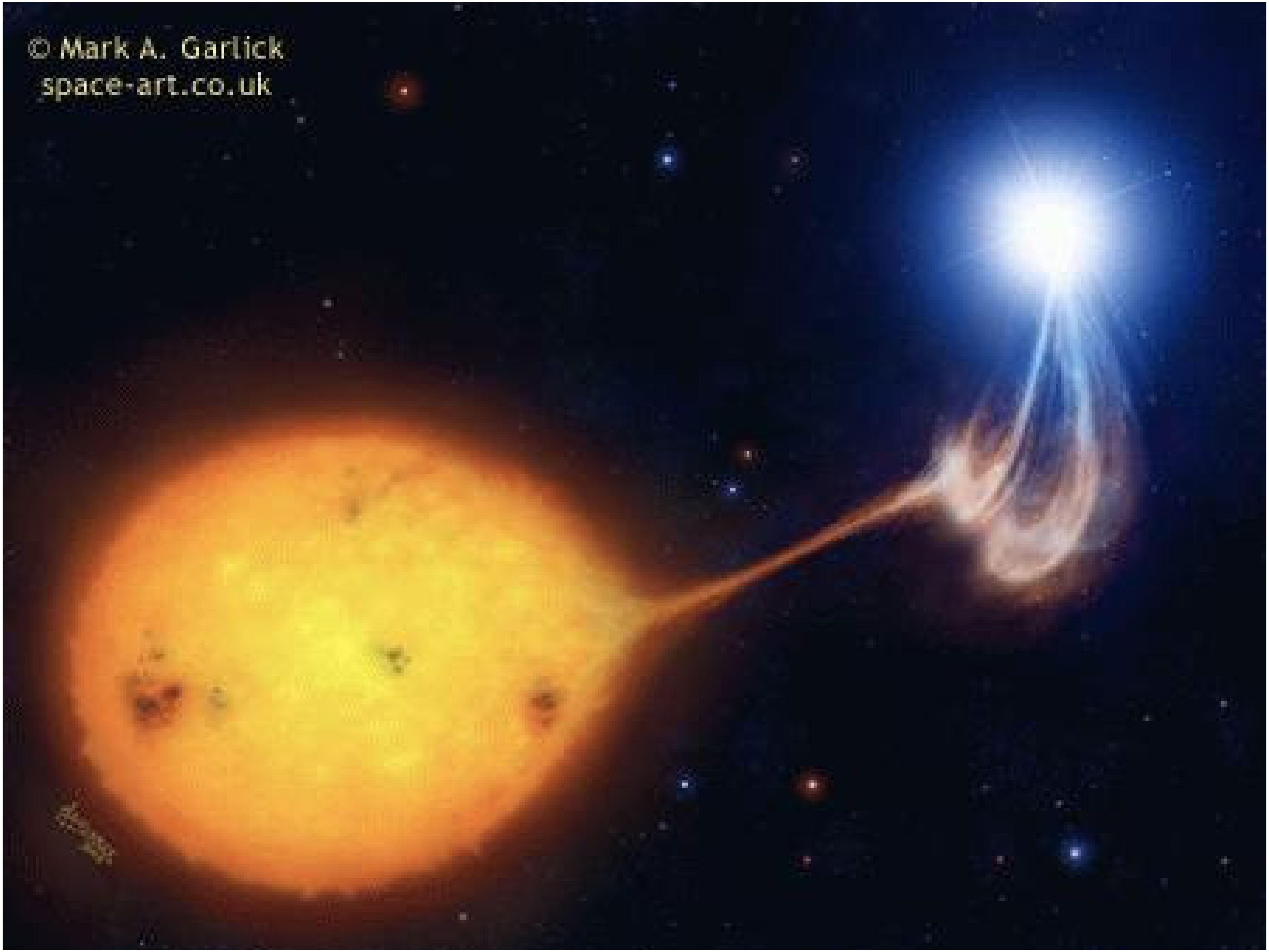
Donor w GaAs



Teoria:

P. C. Makado and N. C. Mc. Gill,

J. Phys. C ***19****, 873 (1986)*



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$B=230$ T, $\gamma=0.01$

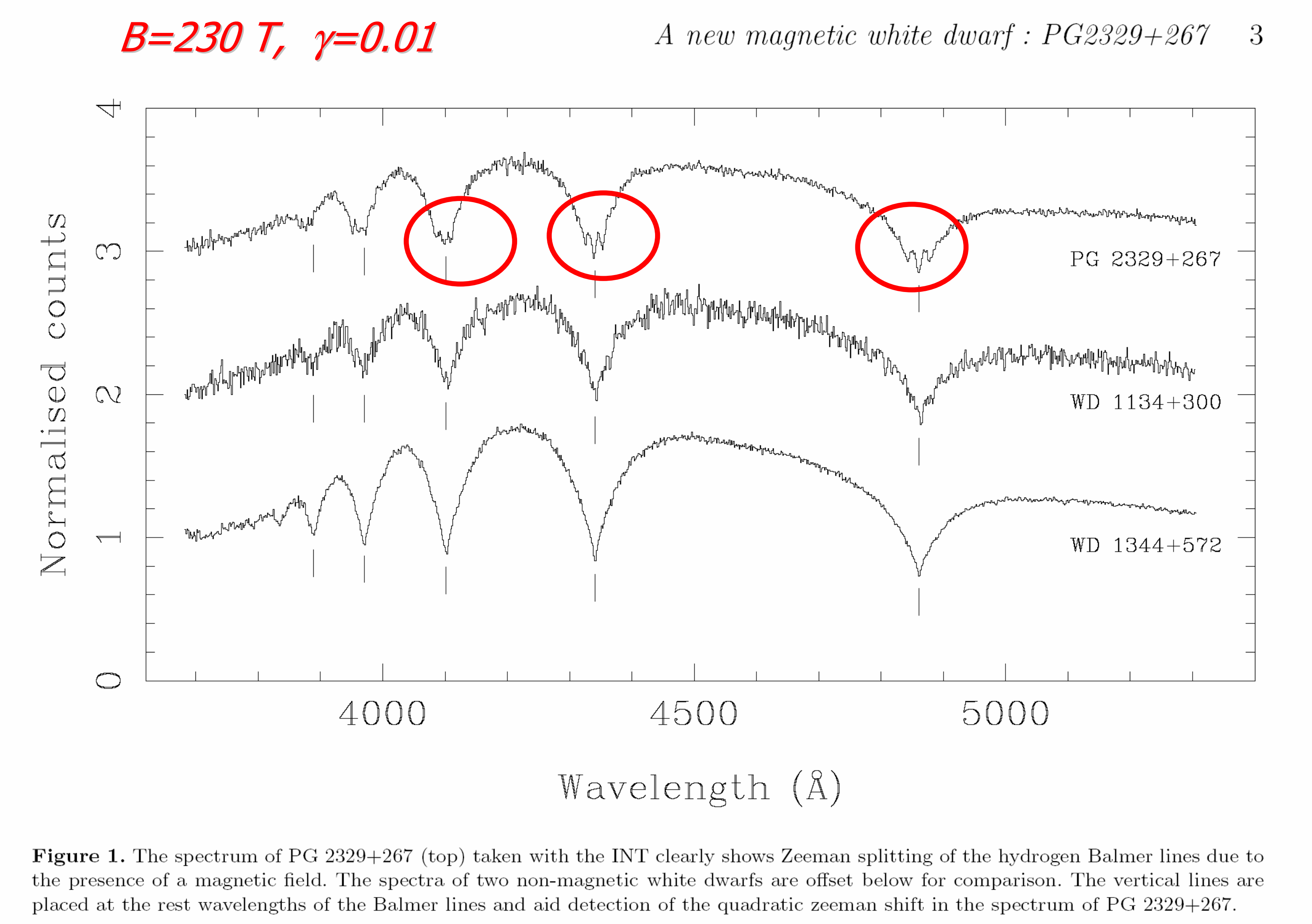

Figure 1. The spectrum of PG 2329+267 (top) taken with the INT clearly shows Zeeman splitting of the hydrogen Balmer lines due to the presence of a magnetic field. The spectra of two non-magnetic white dwarfs are offset below for comparison. The vertical lines are placed at the rest wavelengths of the Balmer lines and aid detection of the quadratic zeeman shift in the spectrum of PG 2329+267.

C. Moran, T. R. Marsh, and V. S. Dhillon (1998)